WIND WAVES AT SEA
BREAKERS AND SURF

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FRONTISPIECE.—A U. S. Navy destroyer rising, after shipping a heavy sea, in Japanese waters. (Official U. S. Navy photograph.)

WIND WAVES AT SEA BREAKERS AND SURF

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19 47

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FOREWORD

The prolific use of amphibious craft and other small vessels during World War II required that a detailed knowledge of wave conditions throughout the world be available to the Armed Services of the United States. To meet this requirement, the Hydrographic Office, under the direction of Rear Adm. G. S. Bryan, USN. (Ret.) and in conjunction with several scientific and governmental institutions, prepared a number of publications that dealt with the occurrence of ocean waves from both the climatic and the synoptic aspects.

Treatment of the climatic aspect involved the preparation of a series of **Sea and Swell Atlases** (H. O. Misc. No. 10,712 series) for the major oceans, the first atlas being published by the Hydrographic Office in 1943.

Treatment of the synoptic aspect hinged on the development of a technique for quantitatively forecasting sea, swell, and surf conditions. This program was initiated by Dr. H. U. Sverdrup and Dr. W. H. Munk of the Scripps Institution of Oceanography under a contract with the Directorate of Weather, Army Air Forces, in 1942. In 1943, the work was transferred to the Navy Department and continued under contracts with the Bureau of Ships and with the Hydrographic Office. By late 1943, the Hydrographic Office issued the first forecasting manual, **Wind Waves and Swell; Principles in Forecasting** (H. O. Misc. No. 11,275). Following expansion of the work which included establishing related contracts with other institutions, a sister volume, **Breakers and Surf; Principles in Forecasting** (H. O. Pub. No. 234) was issued in 1944. Since the end of hostilities, the Hydrographic Office has been able to publish **Wind, Sea and Swell; Theory of Relations for Forecasting** (H. O. Pub. No. 601).

Wind Waves at Sea, Breakers and Surf, the first popular book on the subject in more than a decade, develops further the Hydrographic Office series of publications dealing with sea, swell, and surf conditions. It is particularly fitting that the senior author should be Dr. Bigelow, who, as chairman of a special committee appointed by the National Academy of Science, was instrumental in suggesting that the United States Navy review how it might best assist in the acquisition of basic knowledge about the oceans. As a result of this committee's work, the Secretary of the Navy appointed the Schofield Board; and it is the work of this board during the year 1928 that provides the basis for the program in oceanography now being carried out by the

Navy. Dr. Edmondson, the junior author, participated in wave investigations carried out at the American Museum of Natural History in New York City and at the Woods Hole Oceanographic Institution between the years 1942–45.

This book not only incorporates much of the published findings of recent date but also includes part of the unpublished work carried out under various wartime Navy contracts with the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, and the Department of Mechanical Engineering of the University of California at Berkeley, as well as studies conducted by the Beach Erosion Board of the Army Engineers.

Wind Waves at Sea, Breakers and Surf is a detailed and nontechnical discussion of the subject based on the researches of eminent scientists and on the observations of thousands of seafaring men throughout the past century. The mariner will find in this volume much of value that will assist him in the safe and economical operation of vessels on the high seas, in restricted waters, and in the surf zone.

R. O. Glover,
Rear Admiral, U. S. Navy,
Hydrographer.

PREFACE

Anything that disturbs the equilibrium of the water will start a system of undulations; that is, it will produce waves. This will happen, for example, if one drops a stone in the water. A ship as she steams along starts a system of waves; and so does a submarine earthquake, a volcanic eruption, or a rapid change in the barometric pressure of the atmosphere. The gravitational forces that cause the tides also produce waves. Other events that do this, commonly falling under the eyes of seafarers, are a porpoise leaping and dropping back again, or the tail of a flying fish cutting a pattern on the surface in calm weather. But the most familiar cause of waves that furrow the sea is the wind; and it is of these wind waves that this book treats.

Waves force themselves on the attention of everyone who follows the sea. No seafarer can ignore them, whether fisherman, merchant sailor, yachtsman, or member of the naval establishment; nor can the seaside dweller ignore the breakers as they thunder on the beach. It is no wonder, then, that the waves of the sea have attracted attention since time immemorial, or that more or less extended accounts of waves are to be found in many of the texts that have appeared in recent years on seamanship, on oceanography, on meteorology, on shore line processes, on the construction of breakwaters, and on the protection of beaches from erosion. Waves also have been the subject of many theoretical studies. Yet, no simple, comprehensive account of wind waves from the standpoint of the man at sea has yet appeared in the English language. And it is in the hope of filling this gap that the following description is offered.

Most of the information here presented has been drawn from published sources. We also owe a debt of gratitude to many persons for assistance, especially to Dr. H. U. Sverdrup for his kindness in reviewing some of the theoretical discussions and to Capt. Fenner A. Chase, Jr., AUS, of the Hydrographic Office, Navy Department, who has aided in the editing of the manuscript. We wish it expressly understood that we have made no contributions to the theory of waves. But we would not have dared to undertake the task, if we had not observed the behavior of waves at sea, from large craft and from small, in various parts of the world, under various conditions of wind and weather; or if we had not had many an opportunity to watch the development of breakers—and to cope with the smaller sizes—off beaches of various shapes, off rocky coastlines, and over submerged ledges.

Chapter 1

THE PHYSICAL NATURE OF WIND WAVES

It is difficult to frame a definition, in everyday terms, that will cover all the types of phenomena that are commonly named "waves." As applied to the surface of the sea, however, they may be defined as successive ridges with intervening troughs or valleys which, in the case of wind waves, advance in undulatory motion. Our knowledge of the processes by which the waves of the sea are generated and subsequently developed is still far from complete, in spite of all the attention that has been devoted to the subject. There are two reasons for this. In the first place, it is extremely difficult to take accurate measurements of waves or to analyze their complex contours at any given moment from a ship at sea, or even from the shore. In the second place, the theories that aim to harmonize such observations as have been made with information of other sorts are still in a fluid state, largely because it has been necessary to assume in most theoretical discussions that waves are produced under ideal conditions such as never exist in the open sea. (For recent summaries of wave theory, as applied to wind waves at sea, we refer the reader to the following publications: Krümmel, 1911; Gaillard, 1904; Thorade, 1931; O'Brien and others, 1942; and Sverdrup, Johnson, and Fleming, 1942.) And difficulties of this same sort also complicate the results of laboratory experiments on waves. Consequently, it is not astonishing that various discrepancies still exist between the characteristics of wave action as deduced by theory and as observed at sea or from the beach. Nevertheless, theory checked against empirical observations has advanced to a point where it is our most reliable guide to the dimensions of the waves that are to be expected under a given set of circumstances. After all, water is very nearly a perfect fluid, and conditions in the open ocean, therefore, do at least approximate the ideal state assumed in classical hydrodynamics; then too, the underlying principles are known for the particular departures from this ideal state that most commonly occur at sea, as for example when waves run from deep water into shoal.

Wind waves present themselves to the onlooker as a series of irregular crests separated by intervening troughs which advance across the surface of the sea one after another in unending succession from horizon to horizon. Depending on the state of the wind locally or on the distribution of wind systems elsewhere, they may range in size from

the tiniest ripples that stir the surface here and there, when a breeze first springs up, to the fiercest of storm seas; or in a flat calm, the glassy surface may heave itself upward at intervals in the long, smooth ridges of a swell that comes from afar.

Owing to the extreme mobility of water, to the fact that truly windless areas seldom reach far, and to the rapidity with which even a light breeze sets up a series of undulations, it is rare indeed that waves of some sort are not running out at sea anywhere, though they may be so low as to escape notice. And it is unusual to encounter a truly plane sea surface of more than a few hundred yards in extent or for more than a brief period of time, even in coastal waters.

The natural impression of anyone viewing waves for the first time—or even after viewing them for years, unless he has paid attention—might well be that the mass of water composing each successive crest was moving bodily ahead across the surface of the sea. But it does not require much study to convince the observer that such is not the case. If he watches the movements of any floating object, such as a piece of wood or a seine cork, when waves are running, he will see that his marker does not drift along continuously as it would if the water in which it floats were constantly advancing, but that it moves ahead only a short distance as it is lifted by each crest, to recede again as it descends into each successive trough at so nearly the same velocity at which it had advanced that it returns almost to its original position (but see below, p. 6, for further discussion of this last point). On the other hand, no argument is needed to convince one that the wave forms do progress, even if the water particles composing them do not do so to any appreciable extent.

In short, two distinct types of motion are combined in the advance of a wave. The one, mirrored by the movements of the floating cork, is the oscillatory motion of the water particles of which the waves are composed; the other is the undulatory advance of the wave form. Waves in their advance indeed recall, though they do not truly parallel, the "waves" that one can see running across a field of grain or tall grass on a windy day, when the tips of the grasses are carried ahead with each gust of wind but then return to their original positions, just as any bit of flotsam nearly does on the surface of the sea. And it is fortunate that this is the case, as has often been pointed out; so rapidly do waves often run that, if the enormous masses of water of which storm waves are composed advanced bodily across the sea, the ocean would not be navigable.

A convincing demonstration of the forward and backward movements of the water particles, with the passage of a wave, can often be obtained if one looks down upon a field of submerged beach grass in an estuarine situation at high tide when the sea surface is unrippled and

small swells are running. The grasses sway forward as the top of each crest passes over them, then sway backward under the following trough, to rise again under the next crest (fig. 1).

If one watches a floating marker in moderately deep water, and if conditions are favorable for estimating how much it rises and falls, and how far it advances and recedes with the passage of each wave, the observer will also see that the length of each of its horizontal journeys is about as great as the vertical distance between the point to which it is raised by the crest and that to which it falls in the trough; this is, of course, equally true of the water particles in which the

FIGURE 1.—The movements of beach grass, over which a low swell is running. (From observations at Cohasset, Massachusetts.)

object is floating, since it is these water particles that carry it to and fro, and up and down.

The motions, however, of our marker and of the water particles are not simply upward-forward with the passage of the wave crests, and downward-backward with the passage of the troughs, but form a curved path, corresponding to the convex contours of the wave crests, and the concave contours of the wave troughs. Further, it has long been established, both theoretically and by experiments (usually carried out by watching or by photographing the tracks of small particles suspended in the water), that the particles actually move along circular orbits, in a vertical plane parallel to the direction in which the wave forms are advancing (fig. 2); when the water is so shoal that the proximity of the bottom interferes with the development of the wave, however, the orbits are rendered more or less elliptical (fig. 3).

It should be emphasized, too, that all the water particles along any given perpendicular are moving in the same direction at any

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given instant, throughout the whole of the depth zone that is affected by the wave. Thus, at the instant of passage of the top of the crest, all the water particles that lie below it are moving horizontally forward. During the passage of the back of the crest, all of the water particles below it are moving first obliquely forward and downward, next perpendicularly downward, then obliquely downward and back-

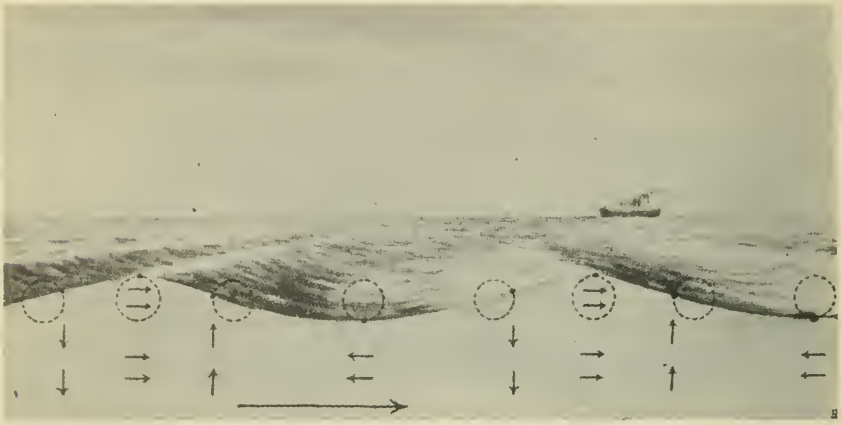

FIGURE 2.—Directions of orbital movement of water particles in different parts of wind waves that are advancing in the direction of the long arrow. (Adapted from Berget.)

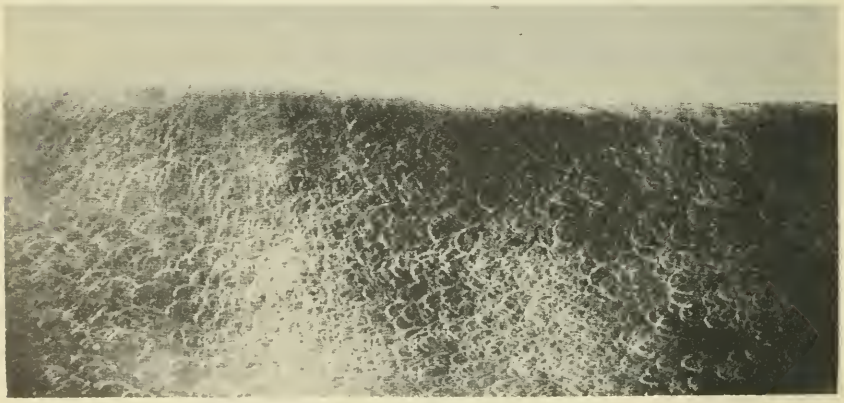

FIGURE 3.—Photograph showing movements of water particles in a wave in water so shallow that their orbits are elliptical. The exposure was for half a wave period. (After Alborn.)

ward. At the instant of passage of the bottom of the trough, all of the water particles below it are moving horizontally backward. During the passage of the front of the next crest, all the water particles below it are moving first obliquely upward-backward, next vertically upward, then obliquely upward-forward, to move horizontally for-

ward again at the instant of passage of the top of the next crest. (See fig. 2.)

It is obvious that if any given water particle is close to the surface of the water the vertical distance between the points that it occupies in its orbit when it is at the top of a wave crest and when it is at the bottom of the succeeding trough is equal to the vertical distance between the crest and the trough. In other words, the diameter of its orbit is equal to the height of the wave from crest to trough and is entirely independent of the length of the wave from crest to crest, or of the speed of its advance.

It is further clear that the velocity with which each water particle circles its orbit is governed (*a*) by the distance the water particle must cover during each circuit and (*b*) by the length of time during which each circuit is completed. The length of the circuit of a water particle at the surface is, of course, equal to the circumference of the orbit, or (the diameter of the latter being equal to the height of the wave) about 3.14 times as long as the vertical height of the wave, crest above trough, at the time. The time occupied by it in each circuit is equal to the time interval that intervenes between the passage of every two successive crests past any given point, for each water particle is at the top of its orbit when each successive crest passes by. This time interval, in turn, depends on the velocity at which the wave forms are advancing, and on the distance from one crest to the next, i.e., on the so-called "period" of the wave, as explained on page 31.

Since there can be no one fixed relationship between the heights of waves and their periods, there is no one fixed relationship between the velocities at which the wave forms advance and the velocities at which the water particles circle their orbits. But the orbits traced by the individual water particles are invariably much shorter than are the distances from crest to crest, because wind waves at sea are always many times longer than they are high. Hence (since the period is the same for the wave as it is for the water particles of which it is composed), the velocities of the water particles around these orbits are always much lower than the velocity at which the wave form is advancing. In the case of a wave, for example, 200 feet long from crest to crest and 10 feet high from crest to trough, each water particle at the surface would trace an orbit of 10 x 3.14 feet, or about 31 feet, i.e., a little more than one-seventh as long as the wave, so that the velocity at which it circled its orbit would be a little more than one-seventh as great as that at which the wave form was advancing. And the longer a wave is, relative to its height, the greater will be the difference between the velocity at which it is advancing and the velocities at which its water particles are circling their orbits. If, for example, the 10-foot wave just discussed were 400 feet long instead of 200 feet,

its velocity would be about 27 knots (p. 35), but the velocities of its water particles would be only about 2 knots. And in the case of long, low swells, the orbital velocities may be as little as 1/100 to 1/200 as great as the velocity of the wave. Consequently, the effects of the alternating following and opposing motions due to the orbital velocities of water particles that a ship encounters are so small as to be negligible; then too, it is only for a very brief instant when the water particles are at the top of each of their orbits (at the crest of the wave), or at the bottom (in the trough of the wave), that their movement is purely horizontal.

We should also note, in passing, that the passage of a wave also involves some actual progress of the water particles in the same direction, as has long been appreciated. In the case of small and not very steep waves, this "heave of the sea," as it is sometimes called, is so small that it is not of practical importance in navigation, though it may be for drifting objects; it is somewhat larger for very large waves, especially if these are very steep. (See table 1.)

TABLE 1.—*Velocity, in knots, of mass transport at the surface for waves of various heights, periods, and lengths*

[Derived from the basic formula $u'=\left(\frac{H}{L}\right)^2 C$, where u' is the velocity of mass transport, H the height of the wave, L its length, and C its velocity]

Period (seconds)	Length (feet)	Height (feet)						
		4	6	8	10	12	20	30
4	82	0.3	0.7	1.3	1.9			
6	184	.1	.2	.4	.6	0.8	2.0	
8	328	.04	.08	.15	.2	.4	.9	2.0
10	512	<.04	.04	.08	.1	.2	.5	1.0
12	738	<.04	<.04	.05	.07	.1	.3	.6
14	1,003	<.04	<.04	<.04	.04	.07	.17	.4

This mass transport, caused by the orbital motions of the water particles with the passage of waves, has no direct connection with the drifts, or currents, that are set in motion by the frictional drag of the wind across the water, though it often is in the same general direction.

THE GROWTH AND DECAY OF WAVES

Whoever watches a passing "cat's paw" of wind as it ruffles the glassy surface on a calm day sees the first stage in the process of wave formation by the wind. But while it is obvious enough why the wind blowing across the surface of the sea should start a mass movement of water in the same general direction, i. e., should set up a wind current it is not so apparent why the wind should first transform the previously level surface of the sea into a series of minute undulations and then build up these tiny crests and troughs to the very considerable

heights to which waves actually rise. The explanation most commonly offered in the older writings is that the gustiness of the wind, pressing upon the surface more strongly in some places and less strongly in others, is responsible by producing depressions and elevations, which then run ahead as waves. And it is certain that this does happen when strong gusts of wind strike the water here and there with what might be termed a plunging motion. This we observed when looking out across a flooded meadow, during a recent gale when each of the more violent gusts instantaneously produced a well-marked depression a few inches deep and several yards across, preceded by an equally well-marked elevation several inches high and advancing at a velocity much greater than that of the smaller wavelets.

It is equally certain, however, that this is not the usual process by which the ripples, that are set up when the surface of the sea is first ruffled, grow into waves, for while gusts of wind are apt to extend over areas at least some yards in extent (as any one can see who watches a field of grain waving under the wind) and are often to be measured in acres or even larger units, the first tiny ripples are only a few centimeters long and few millimeters high. The wave pattern is thus far too small to fit the pattern of gustiness. Further, these tiny ripples are at first astonishingly regular in arcs of long radius; that is to say, they are also much too regular to fit the wind pattern. In fact, no fully satisfactory explanation, how the wind does produce waves from ripples, has yet been offered. There is, moreover, a clean-cut difference in physical nature between the one and the other. The smallest ripples are what is known as "capillary" in nature, i. e., they are due to the surface tension of water, not to the force of gravity. They arise instantaneously when a breeze springs up, to die down when the breeze dies; and they advance the more rapidly the smaller they are, whereas the larger gravitational waves advance the more rapidly the longer they are and may continue to run long after the originating force has ceased to act upon them.

Capillary or "ripple" waves become transformed, somehow, into ordinary gravitational waves when they reach a length of about 0.68 inches from crest to crest, and are moving at a velocity of about 0.76 feet per second. It has been variously reported that it requires a wind of about one half nautical mile per hour to about 2 nautical miles per hour to generate ripples. A stronger wind alters ripples into gravitational waves. Once the alteration has taken place, the waves continue to receive energy from the wind and, hence, to increase in size by the direct push of the wind against the upwind slopes of their crests and by its frictional pull upon the water. The first of these processes acts only as long as the wind is blowing at a velocity greater than that of the waves. And its efficiency in building up the latter depends

not only on how great the difference in velocity is between the two, but also on the shapes of the waves, for the more nearly streamlined these are, relative to the wind, the less hold does the latter have on them.

The wind, however, exerts its friction, not only on the upwind side of the waves, but also on their troughs. But its effect is different on different parts of a wave, for while it tends to speed up the water particles at the crest, because these are also moving in the same direction as the wind, it tends to slow down those in the trough, since these are moving against the wind. And we should point out that if a strong wind be blowing, the effects of its drag on the wave will be the same, even if the wave form be advancing faster than the wind, because the velocity of the latter always is much greater than the orbital velocities of the water particles of which the wave is composed.

The wind also exerts a suction on the leeward slopes of the crests, if the waves are traveling more slowly than the wind, much as it does on the leeward side of a sail. And, while the combination of these actions requires complex computation for its exact evaluation, the net result is that waves continue to gain both in height and in length until they reach the maximum heights to which a wind of given strength can lift them (see p. 20); or if they have already reached that limiting height, they still continue to gain in length. Meantime, newer and smaller waves are constantly being formed on the older and longer ones, into which they then become incorporated, and so on throughout the period during which the waves are gaining energy from the wind. Thus each of the higher crests to be seen at any given moment is really a combination of an indeterminate number of smaller waves of successive generations.

Every seaman knows that after a blow passes, the storm waves that accompany it die down before long, and that a counterwind knocks the sea down very soon indeed. At first sight, this might seem to contradict the rule stated above, that waves of oscillation continue to run, once they are set in motion by the wind. But there is no real contradiction, for it is only when the wave is not opposed by any counterforce that it conserves its energy and hence its form. And it is obvious that a wave is opposed, not only by the interference of any cross sea that is set in motion when the wind changes, but still more strongly by the counterthrust and counter drag of a wind that springs up against the run of the waves. A strong wind from a new direction may, in fact, flatten the waves with spectacular abruptness. Many times we have seen a tumultuous sea killed in this way within a few hours, as has everyone who has traversed the more stormy parts of the ocean; nor is there anything astonishing in this.

The positive difference in velocity, for example, between a counterwind of 20 miles per hour and the rate of advance of a wave no more

than 100 feet long (i. e., of one advancing at a rate of about 13 knots) would be 33 miles per hour, and anyone knows that even a 10-mile wind is a very decided obstacle to his own advance, if he is walking against it. And even if the wind dies down entirely, still the waves are opposed by the resistance of the air that they must displace in their advance. The rate at which a counterwind will actually flatten the waves down in any given case, and the rate at which the resistance of the air will do the same to the waves running in a calm, depends largely on the shapes of the waves, by which we mean how nearly streamlined they may be, for it is obvious that the counterpush of a headwind will act much more effectively in this respect on a steep wave and on one of irregular contour than on one that is long, low, and more evenly rounded. And the greater the energy of the wave, the longer will the latter survive. The general rule is that storm seas are reduced much more rapidly in height by head winds or by air resistance than old, low swells are. The latter may even survive a series of head winds, if these are gentle, though a stiff head breeze may kill a swell in short order.

THE DEPTH OF WAVE ACTION

If an observer crumples a ball of paper or white cloth, wets it, and then drops it overside from a ship lying at anchor when waves of moderate size are running past her, or from a pier under similar circumstances, and if he watches as this marker slowly sinks, he will see that it continues to circle in the vertical plane as just described, with the passage over it of successive crests and troughs, for as long as it remains visible. He may be able to watch it make several such circuits, for it may remain in sight for as long as a minute, if the water is clear. (This demonstration of the orbital motion of the water particles in wind waves, first suggested by Hagen, is cited from Krümmel, 1911, vol. 2, p. 2.)

This simple experiment is a visual demonstration of the fact, well-established both by experiment and by theory, that the orbits along which the water particles move continue circular down to the greatest depths to which wave action is perceptible, provided only that the water be deeper than this, as is the case over the open ocean generally. If, however, the water is so shoal that wave action extends right down to the bottom, as may be the case near land, the orbits followed by the water particles become elliptical, until the particles next to the bottom simply surge to and fro without any vertical component of motion at all.

It has long been known that the diameters of the orbits (and, consequently, wave action) diminishes from the surface downward, although the period occupied by each water particle in circling its

orbit remains the same. Theoretically (and this is supported by laboratory observations) this decrease in the size of the orbits is in geometric progression as the depth increases in arithmetic proportion, the diameters of the orbits decreasing by approximately one-half, with each additional increase in depth equal to one-ninth of the length of the wave (table 2).

TABLE 2.—*Diameters of orbital motion, relative to the diameter at the surface, with increasing depth*

[According to the equation $Hd = H\phi e^{-2\pi\frac{d}{L}}$, where Hd is the diameter of the orbit, $H\phi$ the height of the wave, d the mean depth of the particle, L the wave length, e a constant equal to 2.72, and π the constant 3.14. (From Johnson)]

Depth below mean sea level in fractions of wave length	Proportionate diameter of orbit	Depth below mean sea level in fractions of wave length	Proportionate diameter of orbit
0	1	5/9	1/32
1/9	1/2	6/9	1/64
2/9	1/4	7/9	1/128
3/9	1/8	8/9	1/256
4/9	1/16	9/9	1/512

The orbits calculated by this ratio, for a wave 16 feet high and 360 feet long, for example, which would be 16 feet in diameter at the surface, would be 8 feet in diameter at a depth of 40 feet, 2 feet at a depth of 120 feet, and only 0.059 foot in diameter at 320 feet, and so on. Even for a wave 40 feet high, the orbits circled by each particle would be less than an inch in diameter at a depth of 360 feet. And the velocities with which the water particles circle their orbits decrease in a corresponding ratio as the depth increases, because the period occupied by them in so doing is dependent solely on the time required for the passage of two successive crests past a given point and so continues the same no matter what the depth. For example, the orbital velocity of the particles in a wave 10 feet high and 360 feet long from crest to crest, which would be about 3.9 feet per second at the surface, would be about 0.8 foot per second at a depth of 90 feet, 0.17 foot per second at 180 feet, and 0.04 foot per second at 270 feet. The effects of choppy seas 6 to 8 feet high, such as are common when the wind is rising, would not be great enough to be of any practical importance deeper than 40 to 50 feet, or those of waves 100 to 200 feet long deeper than say 50 to 100 feet, while wave action is wholly negligible, even from the theoretical standpoint, at depths greater than the length of the waves in question. The most interesting illustration, from the navigational standpoint, of the decrease in wave action as the depth increases is afforded by the operation of submarines, for these seldom roll or pitch appreciably when submerged deeper than 90 feet. It is for this reason that it is easy to take pendulum measure-

ments of the force of gravity from a submerged submarine—something that can rarely be done from a surfaced vessel because of its uneasy motions. We might note in passing that deep-sea divers have reported being tossed to and fro when working as deep as 100 feet.

The question of the depth to which wave action may extend is also a matter of interest to the student of submarine geology, because movements of the water, so small that they would be of no concern to the seaman, may still be great enough to shift sand, mud, or even small stones about from place to place over the bottom. It is known by experimental measurements that a velocity of 0.3 foot per second is strong enough to move grains of sand or gravel as large as 0.1 inch in diameter, and it is at this velocity that the water particles would, theoretically, be moving to and fro at a depth of 92 feet, in a wave that was 10 feet high at the surface and 200 feet long. In the case of swells no higher but longer, say one 500 feet long, such as are often encountered at sea, the orbital velocities and, consequently, their abrasive power would be as great as this down to a depth of at least 192 feet; the influence would be noticeable to an even greater depth with still longer waves. And the observations that have been made on the depth at which sand and even stones may actually be shifted about on the bottom are in line with the foregoing. Thus, swells have been said to wash stones as heavy as one pound into lobster pots off the mouth of the English Channel in depths as great as 180 feet; rocks weighing several hundred pounds have been reported as moved by wave action in depths of 90 to 120 feet off the western coast of Ireland; and coarse sand is sometimes brought up from 150 feet by storm waves, to be dashed against Bishop Rock Lighthouse, England, to quote a few incidents only. It has even been stated repeatedly—though not on very strong evidence—that wave action may affect the distribution of submarine sediments to a depth as deep as six hundred feet along the slopes that front the continents. But it is generally held that this is about the extreme depth to which wave action affects the water, in any part of the sea or at any time. (For further discussion of this subject, with additional examples and references, we refer the reader to Johnson, 1919, p. 76.)

We ought perhaps to caution the reader, in this connection, that the presence of ripple marks on the bottom, such as have been regarded sometimes as evidence of wave action in deep water, may equally be the result of currents flowing over the sea floor. For example, submarine photographs have proven the presence of ripple marks at a depth of 498 feet in the Gulf of Maine, although the waves that had been running for some days previous had been far too small to have disturbed the sand at so great a depth (fig. 4).

HURRICANE OR "TIDAL" WAVES

One other type of wind wave remains to be considered, namely, the very high and long waves—distinct from swell—that sometimes precede or accompany a tropical hurricane; these have done enormous damage along the coast, at great cost in human life in different parts of the world on many occasions.

The most characteristic feature of waves of this sort (often erroneously called "tidal waves") is that they inundate low coastal areas

FIGURE 4.—Submarine photograph showing ripple marks at the bottom of the Gulf of Maine at a depth of 498 feet. (Photograph, courtesy of Dr. Maurice Ewing, Woods Hole Oceanographic Institution.)

that are not normally subject to overflow by the tides, sometimes to a vertical height of as much as 40 feet, so suddenly and so overwhelmingly at times that there is no escape. It has, in fact, been estimated that such waves (they may come in trains of 2 or 3 or more) have been responsible for more than three-fourths of all the loss of life that has been caused by tropical hurricanes in one part of the world or another.

The wave that overwhelmed the city of Galveston, Tex., on September 8, 1900, at a cost of nearly 6,000 lives and of tens of millions

of dollars worth of damage to property, was of this sort. Again, in November 1932, such a wave cost the lives of about 2,500 persons out of a total population of about 4,000 in Santa Cruz del Sur, Cuba; on September 2 and 3, 1935, a hurricane wave rising 30 feet above ordinary sea level overwhelmed the Florida Keys at a cost of 409 lives; while on September 21, 1938, a hurricane raised the water to such a height along the southern coast of New England that some 600 lives were lost. But these tolls are insignificant compared to 20,000 people wiped out at Coringa on the Bay of Bengal in December 1789; or 50,000 lives lost and 100,000 cattle drowned at the mouth of the Hoogly River in 1864; or—greatest catastrophe of the sort on record—20,000 boats destroyed, of one kind or another, and about 300,000 people drowned on the shores of the Bay of Bengal by hurricane waves on October 7, 1737. (For a further account of hurricane waves, see Tannehill, 1938, pp. 30–43.)

It is certain that waves of this class are not ordinary waves of oscillation. Probably, they more nearly resemble what are known as "waves of translation" (p. 115), for the inundation is caused by a tide-like movement of a vast mass of water up a shelving shore. And this explanation is supported by the fact that similar inundations—though on a much smaller scale—sometimes take place in shallow sounds, when the water that has been "banked up" as it were by a gale on the one shore, is driven suddenly against the opposite shore by a shift in the direction of the wind. Events of this sort are well known, for example, in Pamlico Sound, North Carolina, when a southerly gale or hurricane shifts suddenly to the northwest. Many of the fish houses standing on piles in the shallow waters of the eastern side of the sound, and also more permanent dwelling houses on the beach, were washed down or damaged in this way by the August hurricane of 1917.

Chapter 2

THE DIMENSIONS OF WAVES

The dimensions of waves, by which their shapes and sizes are usually defined, are:

a. Height, i. e., the elevation of each crest above the succeeding trough, expressed here in feet.

b. Length, from one crest to the next, also expressed here in feet.

c. Velocity at which the wave form advances across the sea, expressed here in knots.

d. Period, i. e., the length of time required for the passage of two succeeding crests passing a stationary point, stated here in seconds.

Many measurements, more or less reliable, of the dimensions of waves have been made at sea in various parts of the world and under various conditions. Among them we might mention, especially, the series made by Lt. A. Paris on French naval vessels in the Atlantic Trade Wind Belt and the southern West Wind Belt of the Indian Ocean, in the East China Seas, and in the western Pacific; by R. Abercrombie in the West Wind Belt of the South Pacific; by the officers of the German research ship *Gazelle* in the North Atlantic, South Atlantic, and Indian Ocean; by G. Schott, during a voyage on a sailing ship in the North Atlantic, South Atlantic, and Indian Ocean in 1891–92; those by Lt. O. Gassenmayr of the Austro-Hungarian Navy on the *Donau* in the Atlantic in 1895; those by V. Cornish in the North Atlantic; especially the very large series of measurements by American officers that were taken during the years 1883–87 and assembled by Capt. D. D. Gaillard of the United States Army; and the dimensions derived by A. Schumacher, from stereophotogrammetric pictures taken of waves during the *Meteor* Expedition to the South Atlantic, as well as from the liner *Deutschland* in the North Atlantic. The dimensions of waves have also been the subject of many theoretical discussions.

THE HEIGHTS OF WAVES

The question, how high are the waves at sea, is one to which very various answers have been given, partly because it is difficult to measure wave heights exactly on shipboard, partly also because three rather distinct problems are involved: the relationship between wave heights and the character of the wind; the heights of the common run of waves at different times and places; and the heights of the largest waves that accompany severe and prolonged gales.

The last of these three problems has received the most attention, no doubt because exceptional and spectacular phenomena are naturally the most impressive, especially if they involve imminent danger to human life and property, as really large storm waves do. But the heights of the common run of waves is of equal or greater importance from the practical standpoint, because the seaman has to do with these every day that he is at sea, but may never, in a lifetime, encounter waves of the great heights that are sometimes reliably reported, even if his voyages regularly cross and recross the stormier parts of the ocean in stormy seasons. The relationship that the heights of waves bear to the wind is also of concern, not only from the theoretical standpoint, but very directly from the practical, as indicating the general dimensions of the waves that are to be expected in different parts of the ocean and at different seasons, according to the prevailing conditions of the weather. And discussion of this phase of the problem is the logical introduction to any account of the heights of the waves that ships do actually meet.

The heights of waves are determined by the strength of the wind, combined with the length of time during which a wind of any given force may have been acting on them. It is a matter of common knowledge that high winds do not generate high waves instantaneously, but require a considerable period to do so. Since the waves are constantly advancing, meanwhile, the time during which the wind may have been acting upon them is proportional to the distance that they have run, or to the "fetch" as this is termed. And it is for this reason that the sea is always smooth under the windward shore, no matter how strong the wind nor how long it may have been blowing, with the waves increasing in height out from the land. In other words, large waves can develop only in comparatively broad bodies of water. The rate at which waves gain in height, under winds of different strengths, has been much discussed and the values given in table 3 are taken from one of the most authoritative attempts that has been made to discover empirically the maximum heights of the waves that winds of different strengths ordinarily produce (given sufficient time and fetch).

The growth of waves in relation to the wind has also been subjected to theoretical analyses. These yield the most trustworthy information now available as to the rates at which waves grow in height under winds of different strengths, for the fact that waves are constantly advancing has so far prevented any one from bringing the growth of a wave under close observation.

The theoretical relationship between height of wave, strength of wind, and duration and fetch of the latter is summarized in tables 4 and 5.

TABLE 3.—*Probable maximum heights of waves with winds of different strengths, combined from various observations at sea*

[Adapted from Krümmel]

Wind		Wave height	
Meters per second	Nautical miles per hour	Meters	Feet
4	8	0.8	2.6
6	12	1.4	4.6
8	16	2.4	7.9
10	19	3.5	11.5
14	27	6.0	19.7
16	31	7.5	24.6
18	35	9.1	29 9
20	39	10.9	36.0
22	43	12.0	39.4

The theoretical relationship between heights of waves and strengths of winds agrees fairly closely with the relationship between wave heights and winds of different velocities, up to 40 miles per hour, that have actually been observed. (See table 3.) But we may point out that the statement, sometimes made, that the heights of storm waves, in feet, average 0.6 to 0.8 of the velocity of the wind, in nautical miles per hour, is not borne out by either tabulation. And the heights of waves, as observed, differ considerably from the theoretical values for stronger winds. Thus the theoretical height of waves for a 56-mile wind is 63 feet, whereas it has been the repeated experience of observers at sea that the upper limit for the average run of waves that accompany winds of 50 to 60 miles per hour, such as are not infrequently encountered during severe gales, is not more than about 40 feet at most. And waves higher than this are unusual, no matter how high the wind, unless indeed two large waves chance to unite (p. 25).

This discrepancy results in part from the fact that the theoretical values, given in tables 4 and 5, are for the highest waves, and these have seldom been actually measured. But the chief reason why waves are seldom as high as should theoretically be possible during severe gales is that winds stronger than 40 to 50 miles per hour seldom blow in a uniform direction far enough for them to produce waves more than 30 to 40 feet high or so. Thus the effective fetch (p. 19) for winter gales in the North Atlantic is not often more than 500 to 600 miles, or enough for the waves produced by a 40-mile gale to rise to only about 32 feet, or three-fourths of the height possible with a wind of that strength over an unlimited fetch. And a fetch of even 800 miles, such as develops occasionally in the North Atlantic with a prolonged gale, is no more than is needed for a 50-mile wind to produce 50-foot waves. But the effective fetch is longer still in Atlantic gales on rare occasions, as it more often is in the North Pacific, and the

general run of the waves may be expected to rise then to the maximum heights possible for 40- to 55-mile winds, i. e., to 55 feet or even higher. It is because the winds in the tropical hurricanes of the Atlantic and in the typhoons of the Indian and western Pacific Oceans do not blow far in any one direction that these—the most violent storms of all—do not produce the highest waves. A case in point is the much longer fetch of the westerly storm, in high latitudes of the Atlantic, illustrated in figure 6, as contrasted with the wind of the tropical cyclone that was centered north of Puerto Rico and of Hispaniola on the same day. And while the Trades do blow along fetches long enough to allow their waves to develop fully, they are not strong enough to generate very high waves. (See table 6.)

TABLE 4.—*The heights of waves, in feet, theoretically produced by winds of various strengths blowing for different lengths of time* [1]

Wind velocity, nautical miles per hour	Duration in hours						
	5	10	15	20	30	40	50
10	2.0	2.0	2.0	2.0	2.0	2.0	2.0
15	3.5	4.0	4.5	5.0	5.0	5.0	5.0
20	5.0	7.0	8.0	8.0	8.5	9.0	9.0
30	9.0	13.5	15.5	17.0	18.0	18.5	19.0
40	13.5	21.0	25.0	27.5	31.0	32.0	33.0
50	18.0	29.0	36.0	40.0	46.0	48.0	50.0
60	23.0	37.0	46.0	53.0	61.0	66.0	70.0

TABLE 5.—*The heights of waves, in feet, theoretically produced by winds of various strengths blowing over different fetches* [1]

Wind velocity, nautical miles per hour	Fetch in nautical miles					
	10	50	100	300	500	1,000
10	1.5	2.0	2.0	2.0	2.0	2.0
15	3.0	4.0	4.5	5.0	5.0	5.5
20	4.0	6.5	8.0	9.0	9.0	9.5
30	6.0	12.5	15.0	18.0	19.0	19.5
40	7.0	17.5	23.0	30.0	32.0	35.0
50	9.0	22.0	30.0	43.0	47.0	52.0

[1] Based on H. O. Pub. No. 604.

TABLE 6.—*Minimum, maximum, and average heights in feet of waves for the Trade Wind Belts*

[After Krümmel, based on measurements by Paris]

Area	Minimum	Maximum	Average
Atlantic Trade Wind Belt	0	20	6
Indian Trade Wind Belt	3	16	9
Western Pacific, including the Trade Wind Belt	0	25	10

Another reason why the waves that accompany strong gales usually are not as high as theory demands is that the increase in the height of a wave is not likely to be continuous throughout the period of its development, as it is represented in tables 4 and 5. This is partly because the wind is gusty and does not blow steadily at maximum strength. But it is also due to the fact that the tops of the crests of waves that are being acted upon by strong winds frequently break, whereupon they lose more or less in height. They then gradually build up once more (as anyone favorably situated can easily see), to break again, and so on. Or they may break continuously along the tops of their crests for considerable periods, which hinders their gaining in height as rapidly as they would otherwise do under a wind of a given strength. This process is discussed more fully on page 31, in connection with the steepness of waves.

A fourth phenomenon directly tending to reduce the heights of the waves in stormy weather, and one with which seamen are familiar, is that the waves often are not at their highest when the wind is blowing the most fiercely, but after it has begun to die down, probably because the most violent gusts carry the tops of the crests off bodily, thus reducing the heights of the waves for the time being.

The relationship between storm waves and the winds that they accompany is complicated further by the fact that the stronger gales of stormy latitudes "commonly come in groups, one succeeding another after a short interval of time. Thus there may be a stormy month during which one cyclonic storm quickly succeeds another, all pursuing the same general track across the ocean. Between times the sea never settles down but heaves with a heavy swell * * * No sooner does a cyclone brew upon the North Atlantic in such a season than the wind in the righthand, rear quadrant of the depression travelling towards Europe immediately steepens this swell into great storm-waves, as happened in the Bay of Biscay on December 21st, 1911 * * *" (Cornish, 1934, p. 29).

Discussion in the literature of the relationship between wind and waves leads to the very important conclusion (borne out by a great number of observations at sea) that waves do not continue to gain in height indefinitely under a given wind, but that there is a limit to their final heights, no matter how long the wind may have been blowing. Moreover the waves grow much more rapidly at first than later, and when a wave has attained about 75 to 80 percent of the maximum height, for a given wind (see table 7), its further growth is very slow.

We should caution the reader here that the word "fetch," as applied to the development of ocean waves, does not mean simply "sea room," as one might gather from a cursory reading of writings on the subject,

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but refers to the extent of ocean over which the wind has been blowing in a comparatively uniform direction, strongly enough to have produced the waves in question.

TABLE 7.—*Maximum wave heights theoretically possible with various wind strengths, and the fetches and durations required to produce waves 75 percent as high as the maximum with each wind velocity*

Wind velocity (nautical miles per hour)	Maximum wave height (feet)	75 percent of maximum height (feet)	Fetch for 75 percent of maximum height (nautical miles)	Duration for 75 percent of maximum height (hours)
10	2.6	2.0	10	5
20	10.6	8.0	90	16
30	23.7	17.8	260	28
40	42.5	31.9	400	34
50	66.2	49.7	740	48

The proverbial rapidity with which the waves rise when a violent squall strikes is not a guide to the rate at which the heights of the waves in question have actually increased, because the squall may have been acting on them for many hours during its advance before reaching the observer. Such no doubt was the case in one recorded instance in the North Atlantic on the 22d of December 1906, when a violent squall, lasting only 4 minutes, resulted in an apparent increase of 7 feet in the height of the waves (Cornish, 1934, p. 9.); and in a second, off Cape Horn on the 23d of January 1926, when an increase in the strength of the wind from four on the Beaufort Scale (23 miles per hour) to about nine (56 miles per hour) between early morning and midafternoon, was accompanied by an increase in the heights of the largest waves from about 2 or 3 feet to about 26 feet.[1]

Waves generated by storms have risen close to their maximum heights by the time they have travelled 600 to 700 miles from the place where they were generated. And a fetch of 900 miles probably is sufficient for the development of the largest of storm waves that have been reliably reported anywhere, no matter how strong the wind.

Thus the waves may be nearly 30 feet high during the most severe blows in the Gulf of Lyons on the south coast of France, where the fetch is only about 400 nautical miles; 29 to 30-foot waves, and higher, have been recorded south of Newfoundland, where the fetch (upwind) was about 600 miles; and 40-foot waves in a heavy swell in the northeastern Atlantic, west of Ireland, where the distance upwind was about 1,100 sea miles to Greenland, or about 1,200 sea miles to the Newfoundland Banks, though the effective fetch may not have been as long as this.

Observations made many years ago on the west coast of Scotland, where the contour of the coast with its off-lying islands makes it fea-

[1] Schumacher, Arnold. 1928. Die stereogrammetrische wellenaufnahmen der Deutschen Atlantischen Expedition. Z. Ges. erdk. ergänz. vol. 3, pp. 117–119, figs. 52, 54.

sible to determine the effective fetch with some accuracy, also led to the conclusion that the waves caused by ordinary winter gales averaged about 1.5 times as high (in feet) as the square root of the fetch (in nautical miles) for distances up to 300 to 400 miles (Stevenson, 1874, pp. 23–26). And the heights derived by this formula, which has been accepted in many of the more recent discussions, correspond fairly well with the heights of waves that have been measured elsewhere in storms or ordinary intensity. Waves, for example, 22 to 23 feet high have been recorded in the Duluth Canal on Lake Superior, where the fetch is 259 nautical miles (Gaillard, 1904, p. 69), as compared with 24.1 feet, according to the formula; and a 30-mile wind has been observed to produce 22-foot waves in the western Meriterranean, where the fetch from the windward shore was about 260 nautical miles, i. e., where 24-foot waves might be expected (Cornish, 1910, pp. 36–40). It is obvious, however, that since this formula takes no account of the strength of the wind, it cannot be invoked indiscriminately, else serious errors will result. Thus a 20-mile wind, which should produce a 7.5-foot wave with a fetch of 25 miles according to the formula, and one of 15 feet with a fetch of 100 miles, would actually produce waves of only about 6 feet and of 8 feet, respectively, at these distances.

The average heights of waves.—The accounts of the early voyagers of the last part of the eighteenth century and of the first quarter of the nineteenth contain many reports of mountainous waves—especially in the stormy Southern Ocean. But it has long been known that their reports were greatly exaggerated. While waves up to 40 to 50 feet high, or even higher, do occur, as described below (p. 23), during severe and prolonged gales, the common run of waves are very much smaller, even in the most tempestuous regions (See table 8.).

TABLE 8.—*Relative frequency of waves of different heights in different regions*

[Adapted from a chart, based on 40,164 extracts from sailing ships' log books, in Schumacher, 1939]

Region	Height of waves in feet					
	0–3	3–4	4–7	7–12	12–20	>20
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
North Atlantic, between Newfoundland and England	20	20	20	15	10	15
Mid-equatorial Atlantic	20	30	25	15	5	5
South Atlantic, latitude of southern Argentina	10	20	20	20	15	10
North Pacific, latitude of Oregon and south of Alaskan Peninsula	25	20	20	15	10	10
East equatorial Pacific	25	35	25	10	5	5
West Wind Belt of South Pacific, latitude of southern Chile	.5	20	20	20	15	15
North Indian Ocean, Northeast monsoon season	55	25	10	5	0	0
North Indian Ocean, Southwest monsoon season	15	15	25	20	15	10
Southern Indian Ocean between Madagascar and northern Australia	35	25	20	15	5	5
West Wind Belt of southern Indian Ocean on route between Cape of Good Hope and southern Australia	10	20	20	20	15	15

The wave heights listed in table 8 mark the North Indian Ocean during the season of the Northeast Monsoon as the quietest extensive region, the waves there being less than 4 feet high for more than four-fifths of the time, less than 7 feet high nearly 95 percent of the time, very rarely as much as 12 feet high, and practically never so much as 20 feet high. The equatorial belts of the eastern Pacific and of the Atlantic oceans are the next quietest, with waves less than 4 feet high for two-thirds of the time and one-half of the time respectively; less than 7 feet high for four-fifths and three-fourths of the time, more than 12 feet for only some 10 percent of the time, and rarely as high as 20 feet. The waves, too, are at least no higher than 4 feet for nearly one-half the time, even in the West Wind Belts of the Northern Hemisphere, whether Atlantic or Pacific, with waves less than 7 feet high for nearly two-thirds of the time; they are less than 4 feet high for roughly one-third to one-fourth of the time, and less than 7 feet high for roughly one-half of the time, in the West Wind Belt of the Southern Hemisphere, whether Indian or Pacific, though this is the most turbulent part of the ocean.

The relative frequency with which waves of different heights have been observed at South Beach, Martha's Vineyard (table 9) with the corresponding tabulation of the height of the surf for points on Long Island, in New Jersey, and in North Carolina (see table 34, p. 151), illustrates the great preponderance of the smaller waves (less than 5 feet high) along the middle Atlantic coast of the United States.

TABLE 9.—*Frequency distribution of waves of different heights at South Beach, Marthas Vineyard, from observations made between November 1943 and April 1944. Each case is the mean of 20 consecutive waves*

Month	Mean height in feet										Total cases	Monthly mean height in feet
	0.0–1.0	1.1–2.0	2.1–3.0	3.1–4.0	4.1–5.0	5.1–6.0	6.1–7.0	7.1–8.0	8.1–9.0	9.1–10.0		
November		2	1	1							4	
December	4	3	1								8	
January	8	22	13	3	1	2	1	1		1	52	2.3
February	4	26	10	6	3	1			2		52	2.4
March	5	20	13	9	3	2	1				53	2.4
April	1	20	10	9	2						42	2.3
Total cases	22	93	48	28	9	5	2	1	2	1	211	
Frequency (percent)	10.4	44.1	22.7	13.3	4.3	2.4	0.9	0.5	0.9	0.5		

The vast majority of waves, in short, are considerably lower than 12 to 15 feet, and waves much higher than 20 to 25 feet are not usual anywhere. Thus the highest measured wave observed on the cruise of the French frigate *Venus* around the world in 1836 to 1839 was about 25 feet, in a case where 2 waves had joined, and otherwise only about 23 feet; these were in the vicinity of Cape Horn. (So far as

we can learn these measurements, made according to the method proposed by Arago [see p. 61] and reported by him,[2] were the first that were ever reported of waves at sea measured by any dependable method.) Similarly, the largest waves observed from H. M. S. *Challenger* during her historic scientific cruise around the world, 1873–75, were only 18 to 22 feet high (southern Indian Ocean between Crozet Island and Kerguelen),[3] while the maximum height reported by United States naval officers from any part of the ocean during the three years, 1883–86, was 25 feet (Gaillard, 1904, p. 76).

The maximum heights of storm waves.—The heights of the largest waves that ships encounter at sea during severe storms is a matter of perennial interest, and published statements have varied widely. We have just pointed out that the vast majority of waves are less than 12 feet high in all parts of the ocean, and that waves higher than 25 feet are not common. But it is well established that waves may grow to 40 or 50 feet—or even higher when a really severe gale extends over an area great enough to have an effective fetch of 600 to 800 miles. The earliest definite measurements by a dependable method of storm waves of that general order of magnitude, with which we are acquainted, were made in February 1841 near the Azores by Lt. de Missiessy, during a violent gale of 2 weeks' duration; he reported wave heights of 43 to 49 feet.[4] More recent reports of waves higher than 35 feet out at sea (mostly from Gaillard, 1904, and Cornish, 1910 and 1934) are listed below.

North Atlantic:

Waves with average heights of approximately 30 feet, the largest (about one in every six) about 43 feet high, observed by Dr. Scoresby midway between Newfoundland and Ireland (lat. 51° N., long. 38°50′ W.) on March 5, 1848.

A maximum height of about 35 feet observed at Peterhead, Scotland, in February 1900.

Waves of at least 40 feet which forced the *Normania* to put back to New York from halfway across the Atlantic, because of the damage done to her upper works, in January 1894.

Waves commonly 29 feet high, but some of them 43 feet high, encountered by the *Ivernia* off the west coast of Scotland on December 7, 1900.

A huge swell, with many waves up to 41 feet high, encountered by the *Minnehaha*, eastbound from New York to Southampton, in latitude 48°54′ N., longitude 18°20′ W., on February 9, 1907.

[2] Arago, D. F. J. 1841. Plus grande hauteur des vagues. C. R. Acad. sci. Paris. vol. 11, p. 326.

[3] Tizzard, T. H., and others. 1885. Rep. sci. res. * * * H. M. S. *Challenger*. vol. 1. Narrative, pt. 1, p. 330.

[4] Arago, D. F. J. 1857. Oeuvres complètes. Paris. vol. 9, p. 550.

Waves of about 40 feet encountered by the *Egypt* and measured by Cornish off the Bay of Biscay in December 1911.

A colossal sea apparently with wave heights of at least 60 feet, as calculated by Cornish from data supplied by the ship's officers, encountered by the *Majestic* southwest of Ireland on February 20, 1923.

A wave of very irregular shape with multiple peaks rising a little above 36 feet, as calculated from stereophotograms taken from the liner *Deutschland*, south of Newfoundland on March 15, 1929 (Schumacher, 1939, atlas, insert chart 29).

North Pacific:

A single wave of at least 57 feet, as calculated from a photograph taken from the United States Fisheries' steamer *Albatross*, off the northwest coast of the United States.

Waves estimated by the commanding officer to be at least 70 feet high, encountered during a prolonged gale of hurricane force by the S. S. *Ascanius* on the run from Yokohama to Puget Sound.

An enormous wave, the highest that has ever been reliably reported, with an estimated height of about 112 feet, encountered during a prolonged period of stormy weather by the U. S. S. *Ramapo* in the central part of the North Pacific on February 7, 1933. [5]

Southern Ocean—West Wind Belt:

Waves of about 30 feet encountered by the *Novara* expedition in the southern Indian Ocean in November 1857.

Waves commonly 30 feet high, with a maximum of 42 feet, near Cape Horn in 1880.

Heights of 21 to 46 feet encountered on the run from New Zealand to Cape Horn in 1885.

A miximum of 37.5 feet reported by Lieutenant Paris in the southern Indian Ocean, between the Cape of Good Hope and St. Paul Island, in 1891.

Waves up to 39.4 feet measured by Dr. G. Schott from a sailing ship in the South Atlantic, also in 1891.

Waves 33 to 36 feet high measured by Captain Chüden in the South Pacific.

Heights of 38 to 45 feet, measured from the *Corinthic* in the southern Indian Ocean in August 1907.

Waves at least 45 feet high, measured from the *Owestry Grange* between St. Paul Island and Kerguelen, also in August, 1907.

Additional instances of very high breakers on one coast or another are given on page 119.

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[5] Whitemarsh, R. P. 1934. Great sea waves. Proc. nav. inst. vol. 60, p. 1100. As this is the highest wave on record, we should point out that the method by which it was measured appears to have been reliable, and that the observer discusses the possibilities of error.

The stormier latitudes of all oceans experience about equally severe gales at one time or another; hence it is not astonishing to find that the largest storm waves that have actually been measured so far have been of about the same heights in the North Atlantic as in the South Atlantic and in the Southern Ocean.

Single high waves and groups of high waves.—Successive waves always differ considerably in height, whether the general run is high or low at the time, and from time to time a wave comes that is considerably higher than the common run. Thus a 6- to 8-foot wave is not unusual when the common run is only 4 or 5 feet, nor are storm waves more than 30 feet high uncommon, even when the average is only 18 to 20 feet while occasional single waves of 50 feet, or even higher, have been observed not uncommonly, as just noted. This is partly because longer and hence faster running waves are constantly overtaking and combining with the slower running ones. This happens when there are two series of waves present, and the phenomenon is called interference. And the chief source for outsize waves of this sort is the union of those that advance from different directions, a frequent event in stormy weather. When this happens, the joint waves may be much higher than those that precede them or that follow them; and there is no way to predict the coming of a wave of this sort. Likewise, when a trough of one series of waves coincides with the crest of another, the resulting wave is considerably lower than most.

During a gale, a ship may also encounter groups of waves, from time to time, that are much larger than the usual run; these may be the product of the more violent squalls with which every gale is punctuated. During the early stages of a blow, when the waves are still so steep that the sea is breaking, a sharp squall often lowers the heights of the waves by temporarily cutting off their tops bodily, as noted elsewhere (p. 19). But the effect of a squall later in the gale, when the waves are relatively longer, is to increase the size of the particular group on which it acts. And, since every gale of any severity is interspersed at irregular intervals by squalls of brief duration, the wave pattern is correspondingly interspersed by groups of considerably larger crests. Cases frequently quoted are a 4-minute squall during a moderate gale in the North Atlantic that was accompanied by waves about 7 feet higher than the ordinary run (p. 20); and another 3 minutes in duration with waves 6 feet higher. The number of individual waves that may combine to form a train of this sort depends on the area covered by the squall responsible for them and on the rate at which it is advancing as a whole, not on the velocity of the wind within it. A squall, for example, advancing at a rate of 20 nautical miles per hour and occupying 4 minutes in its passage (a

common case) would be about 1⅓ nautical miles from front to rear. If the waves averaged, say, 800 feet from crest to crest at the time the squall first developed, it would act on only about 10 of them; it would influence a proportionately greater number if it developed earlier in the gale while the waves were shorter, or a smaller number if it developed after a really long sea was already running. And squalls of wider extent would act upon a correspondingly larger number of waves. A case of this sort is on record for the south coast of England, when a train of 139 large breakers was observed, the product of a single violent squall, with periods so long (average 19 seconds) that the group as a whole must have extended over a distance of 49 miles while they were still out in deep water. This group occupied three-quarters of an hour and it was preceded by five groups, each of four to seven still larger breakers, with average periods of 20 seconds. These groups, occupying one to two minutes had, no doubt, been engendered by a series of 1- to 2-minute gusts, and had outrun the more extensive group produced by the three-quarters of an hour squall.[6]

But the still fiercer gusts, lasting only a few seconds, which, in turn, punctuate every squall, extend over such short distances that they affect only part of one of the individual waves, if the latter have advanced beyond the very earliest stages in their development. Consequently, the sizes of the largest waves produced by a squall correspond to the average velocity of the wind within the latter, not to the very highest velocities to which the wind may rise momentarily.

When we remember that individual squalls travelling at rates of 20 to 40 miles per hour have been shown by self-registering instruments at meteorological stations to have advanced unbroken for distances up to 1,000 miles or more, there is nothing astonishing in the well-established fact that the trains of very large waves that they produce may do the same.

THE LENGTHS OF WAVES

Anyone who has seen ripples grow to whitecaps under a rising wind and who has watched whitecaps develop into a sea knows that the waves grow longer as they gain in height. And the linear distance from crest to crest increases much more rapidly than does the absolute height of the waves, provided the shape of the latter (i. e., the ratio between its length and its height) continues approximately the same, for waves are invariably many times as long as they are high. If a 5-foot wave, 100 feet long (a common proportion of height to length), doubles in size, for example, its length increases by 20 times as much (by 100 feet) as its height (by only 5 feet). And this in-

[6] Cornish, Vaughan. 1929. Waves of the sea, Encyclopedia Brittanica, 14th ed. vol. 23, p. 442.

crease in the length of the wave continues not only as long as its height is increasing rapidly, but even after it has attained the maximum height to which the particular wind in question can raise it.

Table 10, abbreviated from one already published, gives at least a rough picture of the average lengths of the waves to be expected out at sea with winds of different strengths.

TABLE 10.—*Average lengths of waves, observed at sea, according to the strength of the wind*

[Adapted from Krümmel]

Wind			Waves, average length in feet
Beaufort scale	Description	Velocity nautical miles per hour	
2	Light breeze	11	52
4	Moderate breeze	20	124
6	Stiff breeze	30	261
8	Moderate gale	42	383
10	Strong gale	56	827

The averages presented in table 10, which were based on a large number of observations made in different regions, show that ocean waves are usually more than 100 feet long from crest to crest, unless the wind is very light. A similar tabulation (table 11), based on other published measurements of waves from 4 to 46 feet high and more than 60 feet long, also shows that storm waves are not ordinarily longer than 450 to 550 feet in the North Atlantic or North Pacific, and perhaps a little longer, though not averaging so, in high latitudes in the South Atlantic and South Pacific. To find really long storm seas, we must turn to the so-called "Southern Ocean," on the route from South Africa to Australia, where the seas are commonly as much as 600 to 800 feet long in heavy gales. An average of 775 feet has, in fact, been recorded there for an entire day, with occational waves 1,200 to 1,300 feet long.

The lengths just quoted are for waves either still gaining height or at least near the maximum heights to which the wind in question can be expected to raise them. Old swells may be much longer still. And the North Atlantic yields nothing, in this respect, even to the Southern Ocean. Swells as long as 1,320 feet (calculated from their periods, as explained on page 35) have, for example, been observed by French officers in the Bay of Biscay; swells 866 to 1,481 feet long on the west coast to Ireland; others averaging 1,850 feet, and with a maximum of 2,594 feet (by similar calculations), on the south coast of England following a severe Atlantic gale; and still others with a length of 1,914 feet off the Cape of Good Hope many years ago. Swells of 2,719 feet, reported for the equatorial Atlantic,

are the longest yet on record (Krümmel, 1911, p. 49, and Cornish, 1910, p. 92).

TABLE 11.—*Lengths of storm waves observed in different oceans*

[Adapted from Gaillard]

Ocean area	Wave length in feet			Number of cases
	Maximum	Minimum	Average	
North Atlantic	559	115	303	15
South Atlantic	701	82	226	32
Pacific	765	80	242	14
Southern Indian	1,121	108	360	23
China Sea	261	160	197	3

Information as to the lengths of waves is scant for narrower seas. They appear to average somewhat shorter in the China Sea than in the open ocean under similar conditions of wind and weather. And this probably applies also to the Mediterranean, where the longest waves yet recorded in print were of about 328 feet, although higher and hence probably somewhat longer waves have been reported in winter gales.

THE STEEPNESS OF WAVES

The lengths of waves concern the seaman in two ways chiefly: first, as governing the number of individual crests and troughs across which a ship of a given length will extend in different conditions of wind and weather, and second, and more especially, because the length of a wave combined with its height determines its steepness. Steepness may be expressed in two ways, as the ratio of height to length, or as the ratio of length to height. Both methods of expression are used here. The steepness of waves is a matter of very direct concern, if one's vessel is heading into a sea of any considerable size, or if she is running in the trough of the sea.

It is a matter of common knowledge that waves average steeper in the earlier stages of a blow than they do later on (i. e., that they are "choppier"). And theory is in accord with observation in this respect, as appears from table 12.

This tabulation is in line with observations at sea. Off the Cape of Good Hope, for example, a wind blowing for 4 days in a uniform direction has been reported as lifting the average heights of the waves only from 20 to 23 feet on one occasion, though their average lengths increased from 370 to 770 feet (observations by Lieutenant Paris, cited from Krümmel, 1911, p. 64). In another published instance for the Atlantic Trade Wind Belt near the equator, when the largest waves grew from about 5 or 6 feet high to about 10 feet in height, their average lengths increased from about 33 feet to more than 100 feet, i. e., tripled (Krümmel, 1911, p. 64).

TABLE 12.—*The average steepness of waves, expressed as the ratios of their lengths to their heights (boldface, to nearest whole number) and of their heights to their lengths (italics), for winds of different strengths and durations*

[Based on tables 4 and 15]

Wind velocity (nautical miles per hour)	Duration of wind in hours					
	5	10	15	20	30	40
10	**11:1** *0.089*	**23:1** *0.043*	**26:1** *0.038*	**37:1** *0.027*	**52:1** *0.019*	**59:1** *0.017*
15	**12:1** *0.087*	**18:1** *0.057*	**20:1** *0.050*	**23:1** *0.044*	**32:1** *0.031*	**39:1** *0.025*
20	**11:1** *0.090*	**14:1** *0.071*	**17:1** *0.060*	**22:1** *0.046*	**27:1** *0.037*	**31:1** *0.032*
30	**11:1** *0.095*	**12:1** *0.081*	**14:1** *0.069*	**16:1** *0.062*	**21:1** *0.049*	**25:1** *0.040*
40	**10:1** *0.097*	**11:1** *0.091*	**13:1** *0.078*	**14:1** *0.069*	**17:1** *0.058*	**21:1** *0.048*

Observations taken at sea cannot be expected to yield any general rule for the ratio of the lengths of ocean waves to their heights, because low waves may either still be very young—hence, relatively short and steep—or they may represent very old swells, in which case they may be many times as long, relative to their heights. The ratios of length to height among the 2- to 5-foot waves, for example, that are listed in one of the most extensive tabulations yet published (Gaillard, 1904, p. 79), ranges from 10:1 to 125:1 (steepness 0.1 to 0.008). In the case of very high waves, however, the ratio of length to height is never as great as this last, for the fact that they still continue relatively high shows that their proportions have not altered very greatly since the wind commenced to die down. Thus, the largest ratio of length to height for waves of 15 feet and higher (34 cases) that is included in the tabulation cited is 45.6:1 (steepness 0.022). And while the smallest ratio there listed is 10:1 (steepness 0.1), it is certain that waves sometimes are as steep as 7:1, when they become unstable.

Since it is among old—but low—waves that the lengths are greatest relative to the heights, the ratio of length to height would average somewhat greater for low waves than for high, if waves of all stages of growths were combined. But an average of this sort is meaningless in the case of low waves, for the reason just stated, unless indeed the cases that represent waves still in the process of growth can be segregated in some way from those that represent old swells. The need for this precaution has been emphasized before, but no attempt to do this appears ever to have been made for any extensive series of data. And the most that we dare offer in this connection is that the ratio of length to height is usually less than 25:1 (steepness 0.040) for waves that are still growing in height, or of such as have only recently attained their maximum heights, as appears from the following tabulation for 68 published cases falling in this category from different oceans (table 13).

If moderately high swells are included under the heading of "storm waves," as they should be since rough seas are so often running on top of swells, the average ratio is not far from 26:1 (steepness 0.038). When seas have altered into swells as described on page 63, they are often as much as 40 to 100 times as long as high, and swells so old and low that they are recognizable only when they develop into surf along some coastline may even be 1,000 times as long as high. Storm seas and swells varying in steepness from 0.013 to 0.001 have in fact been observed on the south shore of Martha's Vineyard, and probably could be on any other exposed beach to which old swells commonly run.

TABLE 13.—*Maximum, minimum, and mean steepness of waves of different heights expressed as the ratios of their lengths to their heights (boldface) and of their heights to their lengths (italics)*

[Adapted from Gaillard]

Wave height in feet	Steepness			Number of cases
	Maximum	Minimum	Average	
6–9	**24:1** *0.042*	**13:1** *0.077*	**17:1** *0.059*	23
10–14	**24:1** *0.042*	**10:1** *0.10*	**18.6:1** *0.054*	12
20–29	**23:1** *0.043*	**13:1** *0.077*	**15.5:1** *0.065*	5
30–39	**18:1** *0.056*	**11:1** *0.091*	**14:1** *0.071*	11
40–50	**16:1** *0.062*	**14:1** *0.071*	**15:1** *0.067*	2

A further illustration of this general rule is that the average ratios of length to height, among 179 published French observations, were 17:1 for waves shorter than 100 feet, hence still comparatively young; 21:1 for those of 100 to 200 feet, hence older; 25:1 for those of 200 to 300 feet; and 27:1 for those of 300 to 400 feet.

Since, as the waves grow, length and height increase at different relative rates, the steepness of growing waves is a measure of their development, for younger waves are steeper than older ones. It has also been found that the age of a wave that is growing under the influence of the wind may be satisfactorily expressed as the ratio of wave velocity to wind velocity. The relationship between wave age and wave steepness for growing waves is shown in table 14.

The relationship between the heights of waves and their lengths, whether arrived at from measurements at sea or from a theoretical analysis, fails in one very striking respect, for neither method of calculation would suggest that waves are ever less than about 10 times as long as high (steepness 0.1), whereas it is certain that at least the tops of their crests frequently rise to the angle of instability (steepness 0.14), else waves would not break as they so commonly do in windy weather. The discrepancy arises from the fact that the theoretical treatment concerns an average condition.

TABLE 14.—*Correlation between the age and the steepness of growing waves*

[Derived from an average curve fitted to empirical data, in a study by Sverdrup and Munk, Scripps Institution of Oceanography]

Age of wave, expressed as wind velocity/wave velocity	Steepness of wave, wave height/wave length	Age of wave, expressed as wind velocity/wave velocity	Steepness of wave, wave height/wave length
0.1–0.5	0.083	1.0	0.039
.6	.080	1.1	.033
.7	.065	1.2	.028
.8	.054	1.3	.025
.9	.045	1.4	.023

A given wave may repeatedly break; anyone can satisfy himself on this point by looking out over the water when a brisk breeze is blowing, for it is often possible to watch an individual crest steepen until it breaks with a consequent decrease in its height and steepness, then builds up to the breaking point for a second time or sometimes even for a third time before it is lost to view among the neighboring waves. And we have no doubt that every individual wave of a stormy sea breaks in this same way time after time. Thus the history of the compound wave is one of constant alterations in its steepness, alterations of which the theoretical calculations of height and length give no hint and on which no information is available from observations.

THE VELOCITIES AND PERIODS OF WAVES

The fact that is perhaps the most difficult for the layman to accept, when first he observes waves at sea, is that it is not the direct push of the wind against their backs that causes the waves to advance, but that once a wave of oscillation has been set in motion, it will continue to run across the surface of the sea, even in a flat calm. This fact is easily demonstrated; if one drops a stone onto a calm water surface, it is easy to see that the resultant wavelets run out in all directions, far beyond the site of the original disturbance. Perhaps the most striking illustration of the rule that wave forms may continue to advance long after the disturbance immediately responsible for them has ceased, is afforded by the bow waves that a steamer sets up in her passage through the water. These may run so far, that, in thick weather, the first notice a watcher on the land may have that a ship is passing offshore comes when the waves she has set up break on the beach.

Theoretically, the velocity of a freely running wave in deep water is determined chiefly by its length, the rule being that the longer the wave, the higher its velocity. And while the relative steepness of a wave does have some theoretical effect on its velocity, this effect is so small that it can be ignored for all practical purposes. Consequently, an old swell, long but now low, travels at least as fast as the much higher

seas from which it has been derived, or even faster if its length has increased during the period of time since it altered from sea into swell; and there are reasons for thinking that this may happen (p. 66).

It is commonly stated that the velocity of a free wave (i. e., of one that is kept advancing by gravity alone) is proportional to the square root of its length,[7] with the velocity in knots equal to about 1.3 times the square root of the length in feet. And observations on waves at sea agree closely enough with this to show that the formula is a close approximation for waves of ordinary shape.

Actually the velocity depends somewhat on the steepness of a wave, as well, in that higher waves of a given length run a little faster than lower. But this effect is so small that it can be ignored for ordinary waves unless in shoal water (p. 104). (For the complete equation, taking account of steepness, see O'Brien and others, 1942, p. 21, equation 19.)

The facts that the velocity of a wave in deep water is chiefly dependent upon its length, but hardly at all upon its height, and that swells reminiscent of previous storms run at the greatest velocities of all, because of their great lengths (p. 66), make it as misleading to correlate the velocities of waves as a whole with the strength of the wind as it is to attempt similar correlations for their steepness (p. 29), unless their stage of development is known. Any such correlation must therefore take account of the length of time during which the waves in question have been subject to a wind of any given strength if they are to be of any significance whatever. This has been attempted in the following table, adapted and simplified from a recent theoretical analysis of the subject.

TABLE 15.—*Theoretical wave periods (italic), in seconds, and wave velocities (boldface), in knots, in relation to the strength and duration of the wind* [1]

[Based on H. O. Pub. No. 604]

Wind velocity, nautical miles per hour	Duration of wind in hours				
	10	20	30	40	50
10	*3.0*	*3.8*	*4.5*	*4.8*	*4.8*
	9.1	**11.5**	**13.6**	**14.5**	**14.5**
20	*4.4*	*5.8*	*6.7*	*7.4*	*8.0*
	13.3	**17.6**	**20.3**	**22.4**	**24.2**
30	*5.6*	*7.3*	*8.5*	*9.5*	*10.4*
	17.0	**22.1**	**25.8**	**28.8**	**31.5**
40	*6.7*	*8.8*	*10.2*	*11.4*	*12.4*
	20.3	**26.7**	**30.9**	**34.5**	**37.6**

[1] The theoretical relationships between velocity, period, and length, for waves of small steepness, is expressed in the basic equations $T=\sqrt{\frac{2\pi}{g}}\,L$, $C=\sqrt{\frac{g}{2\pi}}\,L$, and $L=\frac{g}{2\pi}\,T^2$, where T is the period, C the velocity, L the length, g the acceleration of gravity, and π the constant 3.14 (Krümmel, 1911, and various subsequent authors).

[7] According to a simplified equation $C=\sqrt{\frac{g}{2\pi}\,L}$, where C is the velocity, g the acceleration of gravity, π the relation between the circumference of a circle and its diameter (approximately 3.14), and L the length; or, taking the average value of g as 32.172 feet per second, C (in knots) equals about $1.34\sqrt{L}$. See also Footnote to Table 15.

It is evident from table 15 that the relationship between the strength of the wind and the velocity of the waves is not a constant one throughout the development of the latter. Thus the statement sometimes made that the velocities of storm waves average about 0.8 as great as that of the wind would apply, theoretically, to a 20-mile wind only while the waves were about 15 hours old; to a 30-mile wind only when they were about 25 hours old; to a 40-mile wind only while they were about 35 hours old. The calculations summarized in table 15 also show the velocities of the waves produced by a uniform wind of any given strength as rising somewhat higher, eventually, than the velocity of the wind. But the few observers who have measured the velocities of storm waves at sea, in relation to the wind, have reported that the advance of the waves is usually somewhat lower than the velocity of the wind as long as the latter is still rising, or as long as it is still blowing at its peak strength. Thus Schott reported the velocity of the wind as varying between 1.17 times and 1.51 times (average 1.32 times) as great as that of the waves, on ten occasions when the waves were measured and the strength of the wind estimated every 2 hours by the Beaufort Scale.[8] Similarly, Lieutenant Paris, of the French Navy, found the velocity of the wind to average about 1.4 to 1.7 times as great as that of the waves in stormy weather when a heavy sea was running.[9] Again, Capt. H. F. David, of the S. S. *Corinthic*, estimated the average length of the waves in August 1907 in the southern Indian Ocean between Kerguelen and St. Paul Island as about 675 feet, corresponding to an average velocity of 40 statute miles per hour, when the wind was logged as 9, Beaufort, or about 44 statute miles per hour (Cornish, 1910, p. 112). Cornish has reported wave periods corresponding to velocities of about 41 knots in the Bay of Biscay during a very strong gale, when the ship's officers estimated the strength of the wind as somewhat greater than 9, Beaufort, or something like 52 knots (Cornish, 1934, p. 4). And waves advancing at 48 to 55 knots (as calculated from their estimated lengths and measured periods) were observed from the U. S. S. *Ramapo*, in the central part of the North Pacific during a February gale when the average velocity of the wind was 60 knots as recorded by anemometer.[10] Zimmerman, however, reports several cases of storm waves running faster than the wind.[11]

The explanation for the greater frequency of waves running more slowly than the wind probably lies in the fact that most observations

[8] Schott, Gerhard. 1893. Über die Dimensionen der Meereswellen. Festschrift Ferdinand Freiherrn von Richtofen zum 60. Geburtstag. Berlin. p. 253.

[9] Paris, A. 1871. Observations sur l'etat de la mer recueillies a bord du *Duplcix* et de la *Minerve*. Rev. marit. colon. vol. 31, p. 121.

[10] Whitemarsh, R. P. 1934. Great sea waves. Proc nav. inst. vol. 60, p. 1100.

[11] Zimmerman, E. 1920. Aufsuchung von Mittelwerten für die Formen ausgewachsener Meereswellen auf Grund alter and neuer Beobachtungen. Schiffbau. vol. 21, pp. 666–668.

are made on smaller, hence younger, waves, and that gales so commonly change direction before the velocities of the waves they produce have risen as high as that of the wind. And it has long been known that as soon as the wind does slacken, the waves outstrip it in their continued advance, so much so, that the waves of an old swell often run at velocities as high as 30 to 40 knots, and sometimes even as high as 60 knots (as indicated by their periods) even during a flat calm.

The nearest approach to a working rule that we dare offer for the velocities of waves, as compared to that of the wind, is the following: Storm seas that have risen nearly, but not quite, to their maximum heights for the wind in question, are usually traveling at a velocity a little lower than that of the wind, if the latter is still blowing strongly; waves may outstrip the wind slightly, even while the latter is near its peak strength, if it has been acting on them for a long period; and the waves invariably run faster than a dying wind.

The waves, produced by a storm in the offing, often give warning of its approach before the wind has begun to blow up where the observer is stationed. The reason is that atmospheric disturbances often advance at rates much lower than the velocities of the winds within them, or than the rates at which the resulting waves advance, as is illustrated by the fact that only 60 out of a group of 264 gales were found to have traveled faster than about 31 knots from the Atlantic toward the coasts of Great Britain (Cornish, 1934, p. 28). The coastwise inhabitants of many parts of the world are, in fact, well acquainted with large waves as forerunners of storms—they were known at one time (perhaps locally) as "death waves" on the west coast of Ireland, and perhaps still are (Krümmel, 1911, p. 92). This general phenomenon is of practical importance in those parts of the world, in particular, where tropical cyclones are to be expected during the "hurricane" or "typhoon" season, for when heavy swells develop there, for which the wind then blowing is not responsible, the chances are that they are coming from an atmospheric disturbance of this sort. This applies in the West Indian-Gulf of Mexico region and off the southeast coast of the United States from July through October; in the southwestern tropical Pacific from December through March and into April; in the Philippine region and the China Sea from June through October; in the Arabian Sea from March through June and from September through December; in the Bay of Bengal from May through December; and in the southern Indian Ocean from November through May. These are the months when hurricanes or typhoons occur most often, not the extreme dates for them.

We have seen it stated that the velocities of these forerunning swells, as calculated from their periods or from their lengths, give the velocities of the winds within the approaching hurricanes, on the

principle that large waves run with velocities not very different from those of winds that produce them. But this is not a safe rule for reasons stated previously, and because the effective fetch within storms of this sort usually is not great enough for the waves produced there to grow to the maximum dimensions theoretically possible for the winds of such high velocities. For example, a wind of only 60 knots (and hurricane winds often blow from 80 to 100 knots) requires a fetch of something like 1,300 to 1,400 miles to produce waves long enough to be advancing at velocities of 50 knots.

Since the period, length, and velocity of a wave are interrelated, the velocities of waves can be calculated from their periods, wherever it happens to be easier to record the period than the length, the working rule being that multiplication of the period in seconds by 3 gives the velocity in knots.[12] A large number of calculations of this sort have been made in many parts of the world, both for storm waves measured on shipboard and for surf breaking on the shore. At first sight, the rule that waves moving at the highest velocities have the longest periods might seem contradictory to everyday experience. The reason it applies is that a wave travelling at high velocity is so much longer from crest to crest than is a wave of lower velocity that it occupies a longer period of time in passing any given point.

Measurements of the periods of waves can likewise be converted into terms of length (since length is the feature of a wave that chiefly governs its velocity) according to the formula that length, in feet, is equal to the square of the period of the wave, in seconds, multiplied by the factor 5.12.

The relationship between the lengths and velocities of waves and their periods is summarized in table 16, and in figure 5.

TABLE 16.—*Theoretical values of velocity (to nearest knot) and length (to nearest foot) for waves of different periods in deep water*

Period (seconds)	Velocity (knots)	Length (feet)	Period (seconds)	Velocity (knots)	Length (feet)
2	6	20	14	42	1,004
4	12	82	16	48	1,311
6	18	184	18	55	1,659
8	24	328	20	61	2,048
10	30	512	22	67	2,478
12	36	737	24	73	2,949

The theoretical values given in table 16, and presented in graphical form in figure 5, agree quite closely with the relationship that has been observed at sea, in different parts of the ocean, as illustrated in table 17. The agreement between the theoretical and the observed values is in fact good enough to show that, for this relationship, the

[12] Actually the equation is $C=3.03T$ where C= the velocity of the wave in knots, and T its period, in seconds. This is a simplification of the formula given on page 32.

former is the more reliable of the two, for it is difficult to take exact measurements of waves at sea.

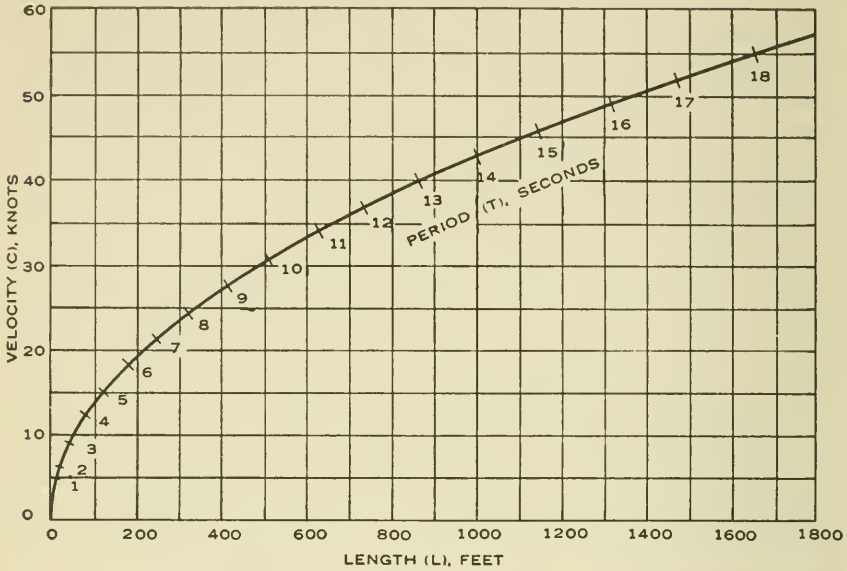

FIGURE 5.—Graphical presentation of the theoretical relationship between wave lengths, velocities, and periods in deep water.

TABLE 17.—*The lengths of waves (as observed and as computed from the observed periods) and the wave periods (as observed and as computed from the observed lengths) in different parts of the oceans*

[Adapted from Krümmel and from Sverdrup, Johnson, and Fleming]

Region	Length in feet		Period in seconds	
	Observed	Computed	Observed	Computed
Atlantic Trades	213	200	5.8	6.0
Indian Ocean Trades	315	341	7.6	7.3
South Atlantic Westerlies	436	535	9.5	8.6
Indian Ocean Westerlies	374	341	7.6	8.0
China Sea	259	282	6.9	6.6
Western Pacific	335	397	8.2	7.5

Incidentally, 26 seconds (reported from the south coast of England) is the longest period yet recorded in print for any wave, though we are informed that waves with periods as long as 30 seconds have been observed at Long Beach, Calif. And velocities of about 79 knots and of about 91 knots that correspond, respectively, to the periods just quoted are the highest that have ever been reported for wind waves at sea. But even these are insignificant as compared with the speeds at which the waves travel from severe earthquakes, such as that of 1868, when the resultant waves in the Pacific had estimated velocities of 300 to 400 knots; or the wave from the Straits of Sunda, or Krakatoa quake of 1883, which must have advanced at a rate nearly

or quite as high, for it is known to have crossed the entire breadth of the Pacific Ocean in 12 hours, while a secondary wave produced by it in the Atlantic Ocean, was recorded on the tide gage at Rochefort on the coast of France, 2 days later (Gaillard, 1904, p. 108, and Berget, 1923, p. 53). The earthquake waves that did severe damage in the Hawaiian Islands on April 1, 1946, offer a more recent illustration. In deep water (16,800 feet) these waves theoretically were advancing at about 430 knots, which agrees fairly well with the recorded interval of 4 hours and 34 minutes occupied by the first of them in travelling the distance of 1,946 nautical miles from their point of origin south of the Aleutian Islands. The waves arrived at average intervals of 15 to 17 minutes, indicating that their lengths in deep water had been about 100 nautical miles. Waves of this sort are so long relative to their heights, i. e., their slopes are so gentle, that they cannot possibly be recognized by ships that meet them out at sea.

At first thought, one might expect that the velocity with which a group of waves advances as a whole would be the same as the velocities of the individual waves that make up the group. And this is true of waves that are still being built up by the wind. In the cases, however, of old swells that continue to run on, as explained on page 34, either after the wind has died down or after they have advanced beyond the limits of the wind system that produced them, the leading waves tend to die out, chiefly because their energy is expended in setting undisturbed water in motion, but partly because of the resistance of the air that the wave crests must displace in their advance. The next wave then takes the lead, and this process of replacement continues progressively. Each wave then takes up energy that was left behind by its predecessor, and, in turn, leaves some of its own energy to be taken up by the next wave. And new waves are formed, successively, in the rear of the preexisting group, so that the position occupied by the latter as a whole, as existing at any given moment, is not as far advanced as it would be if it still consisted of the same individual waves of which it was originally composed. Theoretically, the velocity of such a group of swells is only one-half as great as that of its component waves, individually, if the depth of water is greater than the lengths of the waves, as it actually is over the oceans as a whole.

THE DIRECTIONS IN WHICH WIND WAVES ADVANCE

Wind waves advance at right angles to the sidewise extension of their crests, or at right angles to the chords or tangents of the latter, if the crests are wide enough transversely to show a measurable curvature.

When the wind is rising, the waves that it generates run with it, and they continue to advance in the same direction as the wind, so long as

the latter blows in the original direction. But an alteration in the direction of the wind does not cause waves that are already in motion to diverge at all from their original lines of advance, though it may widely alter their surface contours, as described below (p. 51). It is only when a wave encounters some obstacle, or comes into shoaling water at an angle with the coast line, that the line of advance of any part of its crest or trough is diverted, as described below (p. 155).

The tracks along which wave forms progress also differ in another very important respect from those along which the winds blow, for they are not deflected measurably from their original courses by the effects of the rotation of the earth, whereas winds, unless at the Equator, are thus deflected, to the right in the Northern Hemisphere, to the left in the Southern, so widely that they actually blow at only a very small angle with the isobars (or lines of equal pressure) in the atmospheric disturbances that gave rise to them.[13] The reason for this difference is that the net advance of the water particles of which a wave is composed is so small as to be negligible in this connection, whereas the masses of air that compose the winds do advance bodily.

The end result of the contrast, outlined above, between the directions of waves and of winds is that the former parallel the latter, wherever and whenever the isobars follow straight lines, or curves of very long radius as is characteristic of the winter gales of the West Wind Belts (fig. 6). But the isobars often follow curves of shorter radius. Under such conditions, the directions of advance of the waves, that are generated at successive points along the isobars, diverge from the latter, whereas the winds blow along the isobars so that they veer away more or less sharply from the lines of advance of the waves. The difference in this respect, that may exist in different parts of an atmospheric disturbance, is illustrated diagrammatically in figure 7, where the wave direction would parallel the wind direction within the area between the lines AB and A′B′, because the isobars there are nearly straight. And the waves generated there would be the largest, because it is there that the effective fetch would be the longest. But the winds in other sectors of the disturbance would veer away from the waves because of the curvature of the isobars, so that a very complex series of cross seas, of different generations and running in different directions, would result. It is not known precisely how much the wind must deviate from its original direction to give rise to a distinct new train of waves.

As a rule, too, an atmospheric disturbance does not long remain stationary over the ocean, but advances in one direction or in another,

[13] The direction of the wind averages about 10° to the left of the isobars in the Northern Hemisphere, 10° to the right of the isobars in the Southern Hemisphere. For a readable explanation of the deflective effects of earth rotation, see Pettersen, Sverre. 1941. Introduction to Meteorology. New York. p. 100.

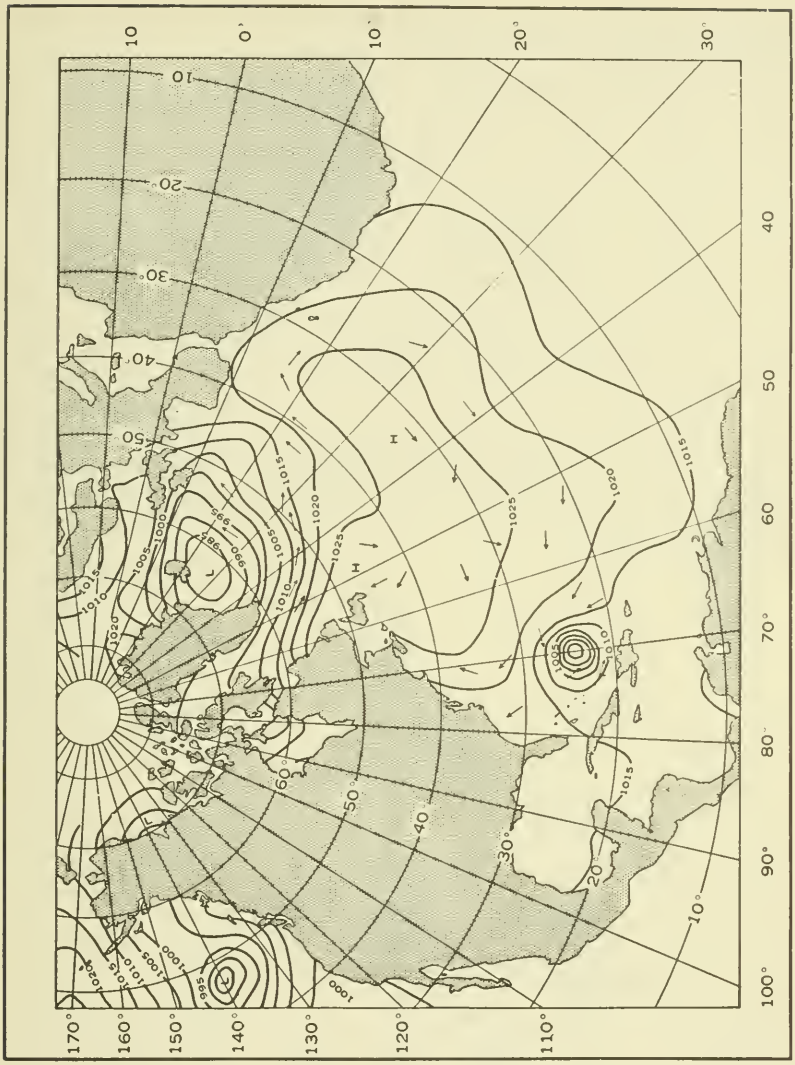

FIGURE 6.—Simplified chart showing the isobaric distribution over the North Atlantic at 1300, Greenwich mean time, September 19, 1938.

so that the relationship between wind direction and wave direction to be expected with the approach of a disturbance depends not only on the shapes of the isobars within the latter, but also on the position of the observer relative to its line of advance. The winds of tropical hurricanes afford a classic example of this. In one such example in the tropical North Atlantic (Tannehill, 1936, pp. 231–238), the direction of the wind is known to have deviated by as much as 60° from that of the waves in the two front quadrants of the cyclonic disturbance, and by as much as 90° to 100° in the left rear quadrant whereas

the direction of the winds of the right rear quadrant nearly paralleled that of the waves that spread thence (fig. 8).

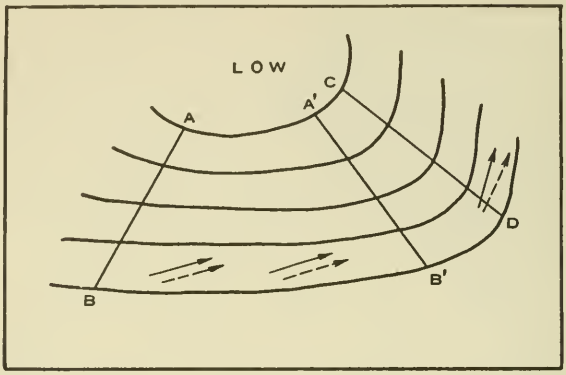

FIGURE 7.—Diagram showing the relative directions of advance of the waves (broken arrows) and of the winds by which they are generated (solid arrows), according to the degree of curvature of the isobars around different parts of a barometric depression.

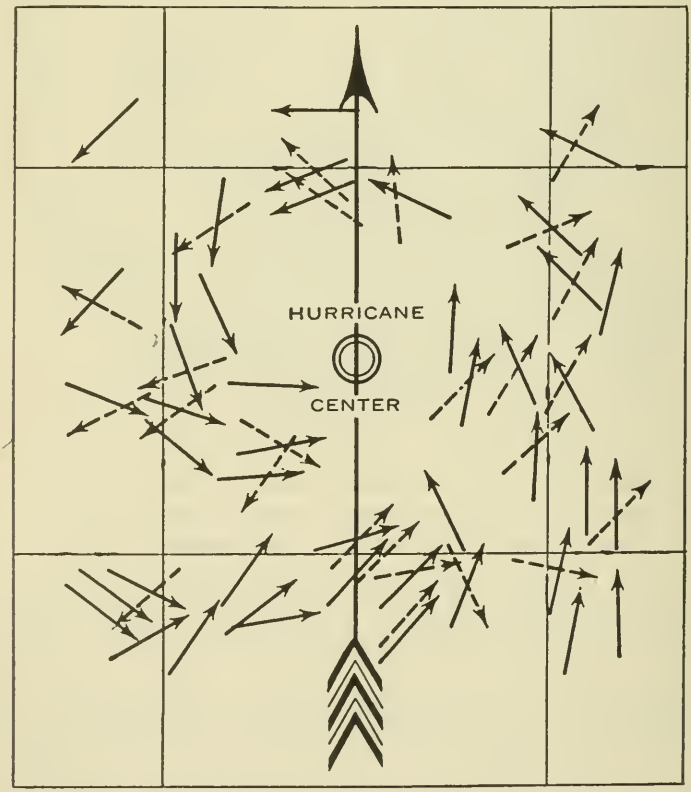

FIGURE 8.—Differences in directions between winds (solid arrows) and waves (broken arrows) in different parts of a tropical Atlantic hurricane. (After Tannehill.)

The persistence of the waves in their original courses, contrasted with the fact that the wind may either blow in a uniform direction across the surface of the ocean for hundreds of miles, be veering in character, or shift abruptly, makes the relationship between the directions of the one and of the other extremely complex. The case is still further confused by the fact that while the velocity of the wind usually does not differ greatly from that of the waves if the weather is stormy, the rate of advance of a wind system as a whole is usually considerably slower than for the winds within it, or for the waves produced by it, so that the waves generated by one system very commonly run to regions that are dominated by a different barometric distribution where the wind blows from some other direction. Thus the possible range between the directions of waves and of winds cannot be reduced to any one simple rule.

Chapter 3

THE CONTOURS OF WAVES; THE EFFECTS OF CURRENTS AND OF SHOAL WATER; THE MEASUREMENT OF WAVES

The Profiles and Surface Contours of Waves

The theoretical profile of a free surface wave of oscillation (i. e., of one that is no longer being driven by the wind but is running on its own momentum, p. 69) is very nearly the shape of a trochoid. That is to say, it follows the curve that would be outlined by the motion of a point within a disc, if the disc were rolled along the underside of a level surface (fig. 9). In a curve of this kind the crest is slightly

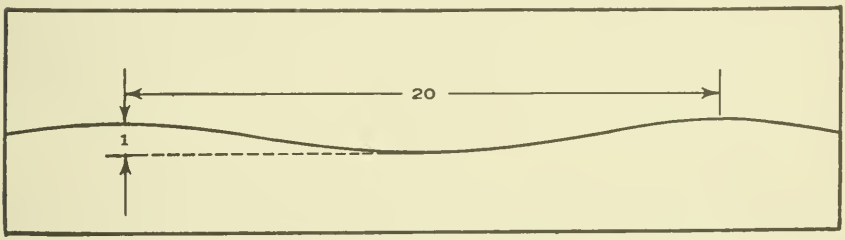

FIGURE 9.—Profile of a wave of trochoid form 20 times as long from crest to crest as it is high from crest to trough.

steeper and narrower than the trough, i. e., the mean level of the water is a little lower than midway between crest and trough, a phenomenon which has some importance in relation to harbor construction but is not of practical interest in relation to ocean waves.

Storm waves still being built up by the wind are usually between 14 times and 24 times as long (from crest to crest) as they are high, so that their average slopes from crest to trough would range from 1 in 7 (8°) to 1 in 12 (5°) if the profile of the wave from trough to crest were a straight line. But it is actually concave in the trough and convex on the crest, so that the slope is somewhat steeper near the top of the latter.

In the case of comparatively long waves, this curvature is so gentle that its effect is very small. If, for example, a wave were 100 feet long and 5 feet high (a common ratio of length to height), its slope would average only about 7° to 8°, along a distance of 15 feet of the steepest part of the actual curve, contrasted with about 5° (or 1 in 10) along a direct line from the bottom of the trough to the top of the

crest. But the angle along 15 feet of the steepest part of the curve of a wave of this same height only 50 feet long would average about 20°, contrasted with about 12° on a direct line from bottom of trough to top of crest (fig. 10).

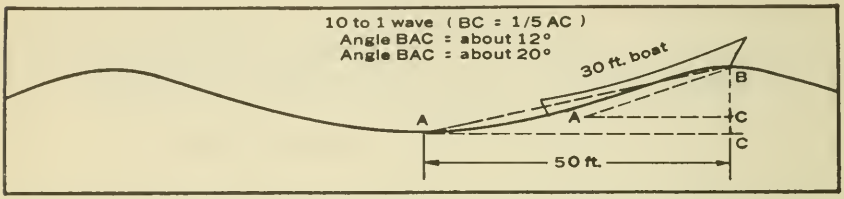

FIGURE 10.—Profile of a wave of trochoid form, 10 feet high and 100 feet long from crest to crest, to show the angle at which a boat, 30 feet long, would be pitched upward on the steepest part of the crest.

Thus, a small boat would be pitched upward at about three times as steep an angle as it mounted the crest of the shorter wave than of the longer, whereas the slope would be only twice as steep in the one case as in the other if it depended solely on the linear dimensions of the wave. It is largely because of this relationship between length, curvature, and slope that relatively short waves—even if well-rounded —may cause small craft to pitch so sharply, and that a "chop" is so proverbially uncomfortable for small-boat navigation.

A trochoid approaches a sine curve in shape if its height is small relative to its length. But the crests become narrower and the troughs relatively longer if the height is large, relative to the length (i. e., if the wave is steeper). If the ratio of length to height decreases to as little as about 7:1 (steepness about 0.014) so that the angle at the crest increases to about 120°, the wave becomes unstable (fig. 11). And

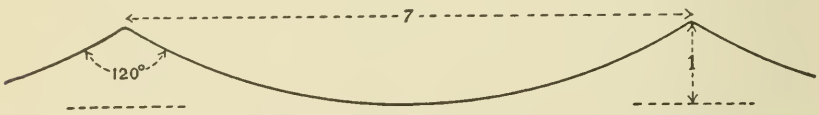

FIGURE 11.—Theoretical profile of steepest possible wave, according to Stokes and Michell. (After Sverdrup, Johnson, and Fleming.)

when the crests approach this angle of instability, they tend to become cycloid in form and therefore very much steeper toward the top, as anyone can see who watches the seas in stormy weather. Waves cannot continue to advance in this shape, but break at the crests, thus losing in height and consequently in steepness as described on page 19.

Very few actual measurements have been made of the profiles of waves. But considerable material is available for such, from published stereophotograms. And these show that the crests of high,

short storm waves are very much steeper than those of relatively longer ones. In one case that has been frequently reproduced (fig. 12), the difference in level between the highest and the lowest points was between 26 and 27 feet in a horizontal distance of only about 190 feet, or a ratio of length to height of only a very little more than 7 : 1. This crest was thus on the point of breaking, and waves of this shape are very commonly seen in stormy weather.

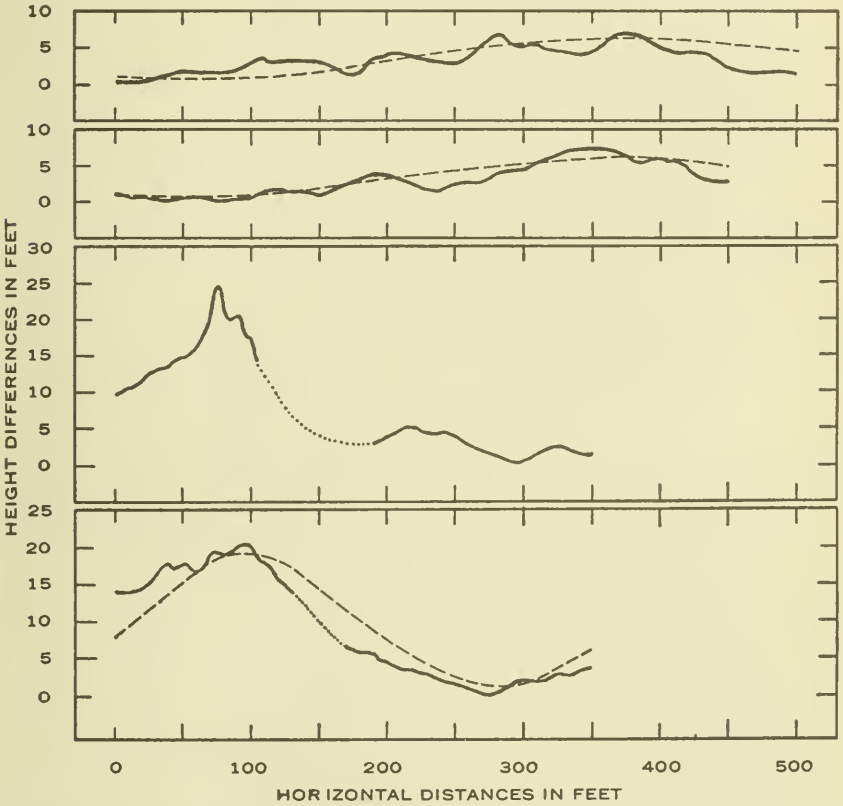

FIGURE 12.—Profiles of waves of different degrees of steepness, based on stereophotogrammetric pictures. The vertical scale is five times the horizontal scale. (Adapted from Schumacher.)

Instability of this same sort can also develop in very small waves as well as in large, whenever the wave is growing rapidly in height, as is usually the case with a rising wind of any considerable strength. The "whitecaps" that develop when a brisk breeze blows up are familiar examples. The seas may continue to break even after they have ceased to increase in height, if the wind continues strong, because the pressure of a high wind is so much stronger on the back of the crest (its windward side) than on its front (lee side) that its crest is

forced forward and falls into the trough ahead. A very strong wind may even blow the water bodily ahead from the crests in sheets of foam or spray, so that waves may not reach their maximum heights until the wind has slackened somewhat (p. 19). In small bodies of water, indeed, severe squalls or winds of hurricane force may lift sheets of spray bodily from the surface in this way, even when the waves are very small, as we have seen ourselves. And the violent squalls that are a usual feature of full gales, when the average velocity of the wind may be 50 to 60 miles an hour, or even higher, often raise the breaking crests so high above the general wave level that if these masses of water chance to fall on deck, lifeboats are often stove in, stanchions carried away, etc.

In short, the old rule still holds and always will, that it is the waves of a storm, not its winds, that the mariner has to fear; also that a high and heavily breaking sea is a dangerous one, whenever and wherever it is encountered.

Lest anyone should think that danger of serious damage by waves to well-found steamers is a thing of the past, we cite the cases of the U. S. heavy cruiser *Pittsburgh*, 100 feet of the bow of which was torn away bodily by an enormous sea during a typhoon in the western Pacific, June 5, 1945, and of three United States destroyers that were lost during a similar cyclonic storm between the Philippines and the Marianas on the eighteenth of the previous December.

The foregoing discussion of the dimensions and profiles of waves has been oversimplified intentionally, by the tacit assumption that waves are more or less regular in shape and that they are distinct, one from the next; also, that their crests extend sidewise for indefinite distances. But this is never the case in reality, for the topography of the surface of the sea is always extremely complex and irregular. Whenever the wind is high, waves of all sizes, from the very smallest up to the highest that have yet developed are intermingled, with neighboring waves differing in shape from comparatively low and long to so short and sharp that they are breaking, or about to do so. Secondary ridges, peaks, and valleys are also to be seen, running on top of what may be called the primary series (figs. 13 and 14), which, in turn, may or may not run in the direction of the wind. Also, it is only when the "seas" have been transformed into "swells" as described below (p. 63) that the individual crests extend far widewise. In stormy weather, on the contrary, their lateral breadth may not be more than three to five times as far as it is from one crest to the next, and sometimes no farther than it is from crest to crest, with their ends merging into the valleys in a wholly irregular pattern. The result is that any profile, transverse to the general trend of the waves, is always a very irregular one, so long as the wind is blowing strongly.

FIGURE 13.—Smaller waves—some of them breaking—running on top of an older swell so large that a Coast Guard Destroyer Escort is largely concealed from view behind one of its crests, to illustrate the complexity of wave contours expected in windy weather. (Official U. S. Coast Guard photograph.)

FIGURE 14.—A moderately heavy sea in the North Atlantic, to illustrate wave contours. (Official U. S. Navy photograph.)

A striking example of such irregularities is to be seen in figure 15, in which the successive contours reveal the presence of several much smaller wave forms running upon the front of a single larger wave that was 18 to 19 feet high from trough to crest. Neither does any one wave reproduce another, as is evident from comparison of the wave represented in figure 15 with the 27-foot wave, the contours of which are laid down in figure 16. And while the topography of the

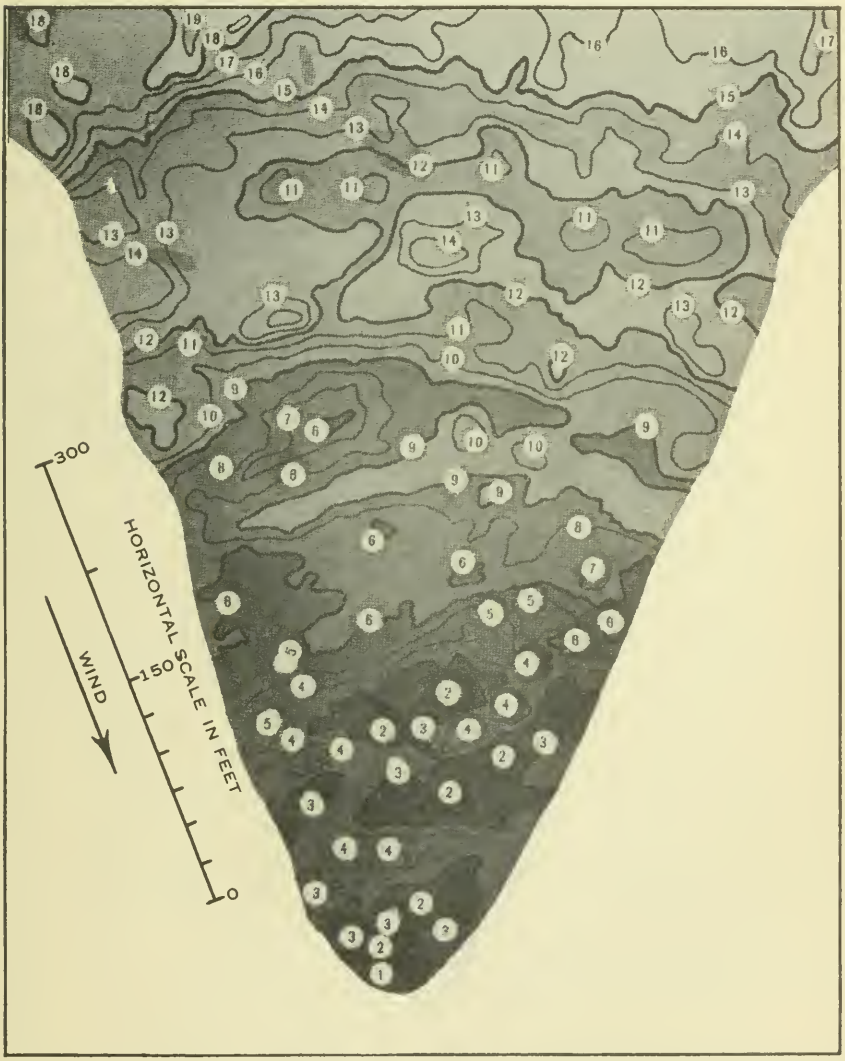

FIGURE 15.—Surface configuration of the front of a wave about 19 feet high, during a rough sea, based on stereophotogrammetric pictures taken off Cape Horn on the morning of January 23, 1926. Contour lines are in feet. (Adapted from Schumacher.)

sea surface is strongest and most complex with high winds and a rough sea, anyone looking out over the water can soon convince himself that the wave pattern is not only irregular, but always constantly changing, even when sea and wind are moderate. It is only in cases of old developed swells and in moderately calm weather that wave crests are well-rounded and that they tend to extend far sidewise across the surface of the sea. And even then, other waves of

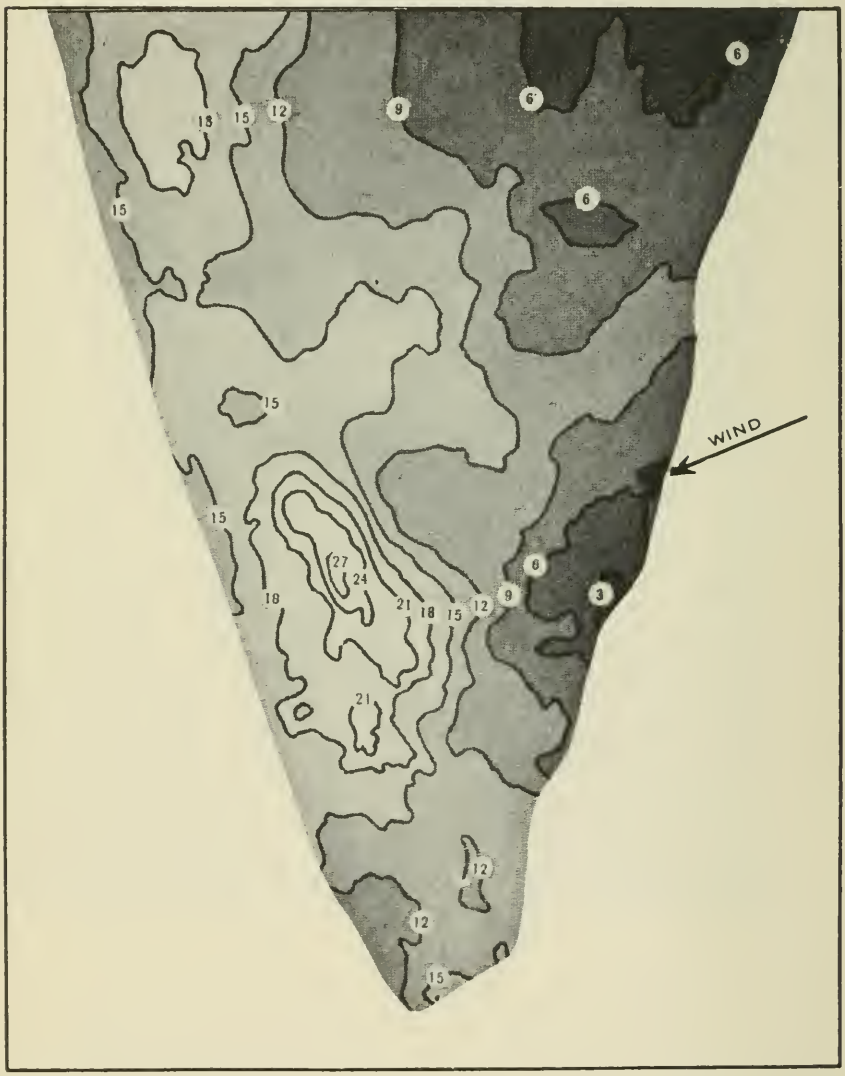

FIGURE 16.—Surface configuration of the back of a storm wave 27 feet high, based on stereophotogrammetric pictures taken on the afternoon of the same day, and at about the same locality, as those on which figure 15 is based. Contour lines are in feet. (Adapted from Schumacher.)

various sizes, smaller or larger, will be running across the older swells in one direction or another if the wind is strong enough at the time to produce a wave pattern (fig. 13). In any case, when two separate trains of waves are present, travelling in different directions, the result of the interference will be a series of peaks rather than ridges. (See Sverdrup, Johnson, and Fleming, 1942, p. 531, fig. 133.)

The most obvious cause for these irregularities is that whenever the wind changes in direction, or when a new wind springs up from a new direction after a calm, a cross sea develops on top of whatever older waves may already be in existence. But irregularities also develop from the immediate effects of a freshening wind, because the latter is never steady, but comes in gusts that vary so widely in strength (also in direction) that every fresh gust sets up a new set of short-crested wavelets on the backs of the older waves. This is true, even in the Trade Wind Belts where the wind is more nearly constant in strength and in direction than it is anywhere else. And it is largely because the new wave systems set up by a dying wind are progressively smaller and smaller that old swells are so much more even in contour than storm waves are (p. 45).

During storms, the contour is still further complicated by the fact that peaks occasionally shoot up to great heights when two waves come together from different directions, as illustrated on a small scale in figure 17. Reports have it, in fact, that the most tumultuous and dangerous seas of all are those that develop in the area of calm air at the "eye" of a tropical hurricane as a result of the interference between the wave trains that meet there. Nautical periodicals contain repeated accounts of the damage done even to well-found ships, steam as well as sail, by the masses of water that may fall on board when such seas break; of decks swept clean of boats and houses, of bulwarks carried away, and of hatches stove in by the mere weight of water. Many a ship has been lost with all hands under such circumstances.

If a strong head wind blows up suddenly, or if the wind suddenly shifts while still blowing strongly, the waves—even very small ones—often break backwards, so that their crests are driven over into the troughs behind. Similarly, a short steep sea, and often a very tumultuous and irregularly breaking one, tends to develop if waves are running against a strong tide or current, since the effect of the latter in such cases is to increase the heights of the oncoming waves, but at the same time to decrease their lengths and thus to render them steeper, as is described more fully on page 53.

THE EFFECTS OF CURRENTS ON THE DIMENSIONS OF WAVES

The preceding pages have taken no account of the possibility that the surface stratum of the sea may be moving in one direction or

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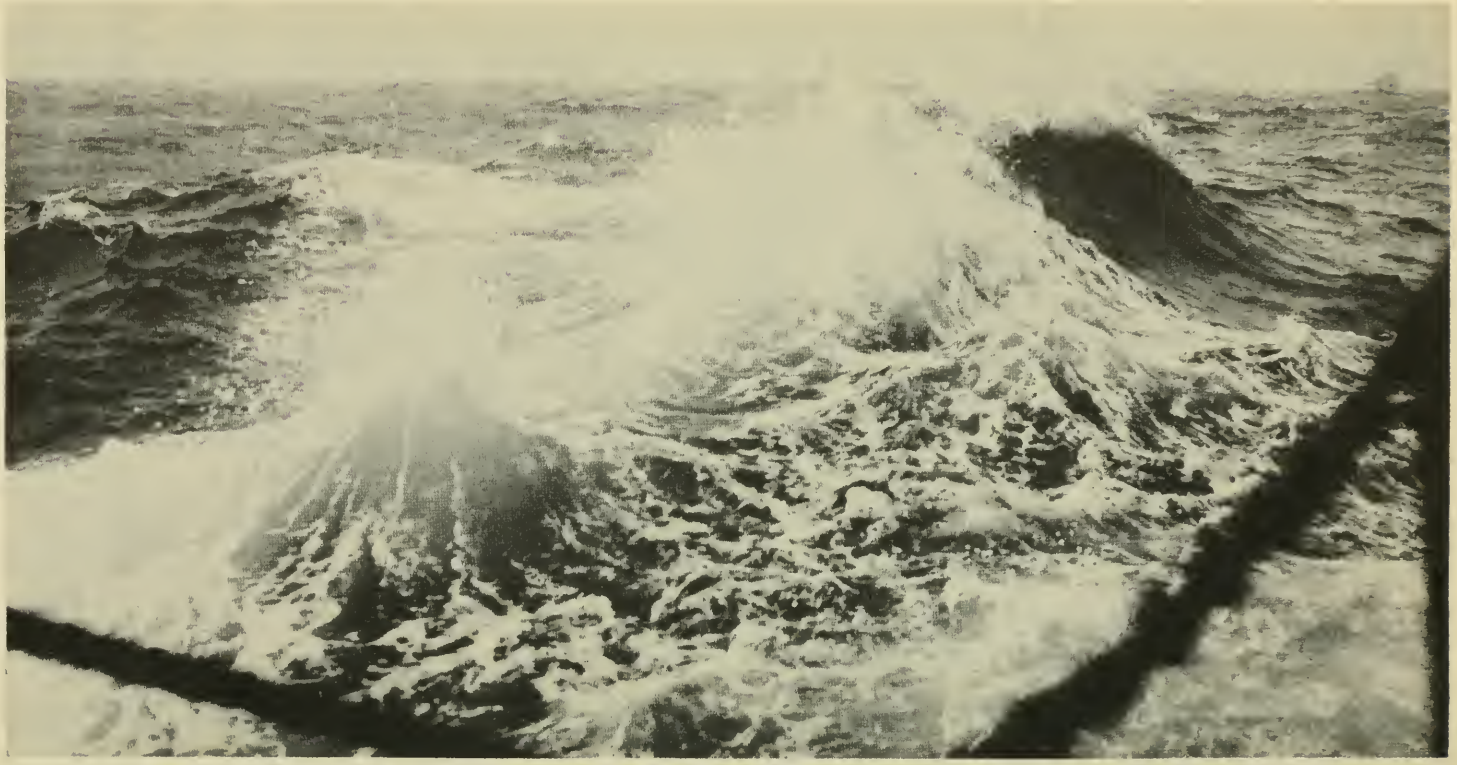

FIGURE 17.—Peaks developed by the interference between a sea of moderate roughness and waves set in motion by the passage of a light aircraft carrier. (Official U. S. Navy photograph.)

another, independent of the motion of the wave forms across it. Actually, however, this is the normal state of the sea, except for very brief periods of time and over very small areas, water being the most mobile of common substances next to air. Therefore, the effects that currents may have on wave motion deserve consideration. The problem, reduced to its simplest terms, is one of the effects on waves of currents that are either contrary or are following, because it is the contrary or the following component of motion that comes into consideration in the cases of currents that are flowing at an angle with the run of the waves.

Briefly, the effect of a contrary current is to decrease the lengths and hence to increase the heights of waves, since the amount of energy is unchanged, thus rendering them steeper. But it does not alter their periods, because it decreases their velocities in the same proportion that it decreases their lengths. The effects of following currents are the reverse, i. e., they increase the lengths of waves and decrease their heights so that the waves are rendered less steep, though again without altering their periods. The degree to which a wave is altered by a current depends on the ratio between the velocity of the wave while in still water and the velocity of the current it encounters, the latter being regarded as positive if it is in the same direction as the wave, negative if it runs against the wave (table 18).

TABLE 18.—*Ratios between the heights, lengths, and steepness of waves in still water and in currents of different relative velocities*

[Based on a theoretical study made at the Scripps Institution of Oceanography]

Ratio between wave characteristics in current and in still water	Ratio between current velocity and wave velocity in still water									
	Contrary currents					Following currents				
	−0.25	−0.20	−0.15	−0.10	−0.05	+0.05	+0.10	+0.15	+0.20	+0.25
Height	2.35	1.75	1.39	1.21	1.08	0.93	0.87	0.82	0.79	0.76
Length	.43	.52	.67	.79	.90	1.08	1.19	1.26	1.36	1.43
Steepness	5.49	3.40	2.07	1.53	1.21	.86	.73	.65	.58	.53

The general rule is, the stronger the current, the greater its effects upon the waves that may be advancing either with it or against it.

According to table 18, if a wave that has a period of 4.2 seconds, hence is 100 feet long in deep water and is travelling at the rate of 13.4 knots, encounters a current flowing in the opposite direction at 2 knots (ratio of current velocity to wave velocity of −0.15), the height of the wave should theoretically be increased by a factor of 1.39 by the time a steady state was reached, but its length would be decreased to 67 feet. The alterations would be smaller in both these respects, if the current were flowing more slowly, larger if it were flowing more rapidly. If the wave in question ran into a following current of the

same velocity, its height would be 0.82 as great as previously and its length 1.28 as great. Thus a contrary current affects the heights of waves much more in proportion than a following current does, a matter of importance in connection with tide rips. For example, the steepness of the 100-foot wave would very shortly be increased by about 2.07 if it ran into a contrary current of 2 knots, and by 1.35 if it ran into a contrary current of only 1 knot. The result is that when moderately steep waves run into contrary currents, the increase in their heights, combined with the decrease in their lengths, may render them so much steeper still as to cause a violently breaking sea. Thus, a head current of 2.2 knots would soon cause a wave that was 5 feet high and 100 feet long, to start with, to steepen to the breaking point.

The effects of currents on the heights of waves are the greater, the shorter the waves and the lower the wave velocities, because the difference between the speed of the current and the original velocities of the waves is less then. If, for example, the wave just mentioned, as encountering a head current of 2 knots, were only 50 feet long, the ratio of velocity of current to that of the wave would be about 0.21, in which case the effect of the current would be to increase the height of the wave by about 1.9 or nearly to double it, if the wave did not break. And for the same reason, the decrease in height in a following current is greater for a short wave of low velocity than for a long one.

The surface currents that are of concern to the seaman, as they affect the shapes of waves, may be classified as "wind drifts," as "ocean currents," and as "tidal currents." It is not necessary for our present purposes to discuss the basic causes for larger ocean currents.

The frictional drag of a wind blowing in a constant direction for more than a brief period soon sets a wind drift in motion, the velocity of which varies according to the strength and duration of the wind, entirely apart from any velocity of mass transport by the waves (p. 6). And drifts of this sort are often so strong that they must be taken seriously into account in navigation, especially in coastwise waters where a slight error in one's dead reckoning may have serious results. In most cases, however, the velocities of wind drifts average only about 1.5 to 2 percent as great as that of the wind,[14] which is not enough for them to have any great effect on the shapes of the waves that may be running either with them, or even against them. The drift, for example, set up by a 20-mile wind would average only about 0.3 to 0.4 knot, which is only about 0.03 of the velocity of the waves that winds of that same strength should, theoretically, generate after blowing for a period of 10 hours. Even if the current were directly con-

[14] Based on a very large number of observations by the U. S. Coast and Geodetic Survey.

trary in such a case, the heights of the waves would be increased by only about 1.06 times. And even in the rare cases when wind drifts do flow at velocities so great that they would steepen the waves measurably if they were contrary, it almost always happens that the waves are running with the drift, because both the waves and the drift are generated by the same wind system. The wind drifts with velocities as high as 1.4 to 1.9 knots with 25 to 55-mile winds, that have been reported at Diamond Shoal Lightship, about 15 miles out from the land southeast of Cape Hatteras, are cases in point.[15]

Tidal currents, like wind drifts, are seldom strong enough out over the ocean basins to cause any noticeable alterations in the shapes of the waves; but they do often run so strongly in continental waters that their effects are notorious for steepening any waves that may be running against them there, and this is true even well out from the land in many localities. Thus the tides run at velocities up to 1 to 1.6 knots on the shoaler parts of Georges Bank, which forms the offshore rim of the Gulf of Maine, while tidal velocities as high as 1.3 knots have also been recorded at Nantucket Lightship, which is stationed at the 30-fathom contour, 41 miles out from the land. And the tides run even more strongly still around many a jutting headland, as it also does in its passage up funnel-shaped bays or through narrow channels and sounds. Tidal velocities at strength up to 1.8 knots round the tip of Cape Cod, up to 2.5 to 3 knots in the Grand Manan Channel at the entrance of the Bay of Fundy, up to 3 to 4 knots in the Golden Gate (entrance to San Francisco Bay), up to 8 to 10 knots in Seymour Narrows, British Columbia, and as high as 9 to 11 knots in the narrow waters between Scotland and the Orkney Islands are well known illustrations.[16]

In cases as extreme as these, a very moderate sea, indeed, may be transformed very abruptly into one that is very dangerous to small craft, upon the advance of the waves into the tideway, if the latter is running against them. And many points, shoals, and bars in various parts of the world owe their local names to this fact; "Pollock Rip" at the entrance to Nantucket Sound, the "Rips" on Nantucket Shoals, "Race Point" at the tip of Cape Cod are familiar examples on the east coast of the United States.

Steep, tumultuous waves also characterize the more swiftly flowing parts of the major ocean currents, whenever the waves there are run-

[15] For tabulations of wind currents with different winds, at Diamond Shoal Lightship and at other lightships along the Atlantic coast of the United States, see Haight, F. J. 1942. Coastal currents along the Atlantic coast of the United States. Spec. pub. U. S. Coast and geodetic survey, No. 230, pp. 55–70, tables 12–15.

[16] These velocities are cited from: Stevenson, 1874, p. 65; Krümmel, 1911, p. 104; Marmer, H. A., 1926, The Tide, New York, p. 99; Bigelow, H. B., 1927, Physical oceanography of the Gulf of Maine, Bull. U. S. Bur. Fish., vol. 40, pt. 2, p. 856; and from various publications of the U. S. Coast and Geodetic Survey.

ning against the current. The proverbially choppy and irregular waves of the Gulf Stream—especially when a northeast wind is blowing against the current—have this source; so, too, the high seas that develop along the easterly edge of the Grand Banks of Newfoundland when southerly winds combat the Labrador Current coming from the north; also off Cape Agulhas, South Africa, with westerly winds, during the season of the year when the Agulhas Current is flowing westward. And many other like cases might be cited in other parts of the ocean where current and wind are opposed.

Another phenomenon of practical importance is that when waves, running against a tide rip or other contrary current, pass out of the latter, they lose height and become smoother with astonishing abruptness, for they then shrink almost instantaneously to the heights at which the winds blowing at the time would have maintained them in still water, while their lengths increase at the same time.

Likewise, storm waves may be entirely knocked down if they strike a strongly running tidal current at right angles, perhaps because of the eddies that are set up along the zone of conflict between the current and the less rapidly moving water outside its influence. The narrow waters between the Shetland Islands and around them afford classic examples of this. But, for some reason, it appears that ocean currents do not have a quieting effect of this sort on wave trains that run transverse to them, for swells originating from storms in the Gulf Stream region of the northwestern Atlantic are sometimes known to run as far as St. Helena in the South Atlantic, which involves the crossing of the North Equatorial Current, of the Equatorial Countercurrent, and of the South Equatorial Current.

ALTERATIONS IN THE DIMENSIONS OF WAVES OVER A SHOALING BOTTOM

Waves that are generated out at sea are not interfered with by the proximity of the bottom, for this happens, in measurable degree, only where the depth of water is less than one-half as great as the lengths of the waves (or than the lengths to which these would have grown, if unhampered); and storm seas are seldom more than 600 to 800 feet long, whereas the break in slope at the margin of the Continental Shelf lies at a depth of about 600 feet in most parts of the world. But when waves run in from the open sea toward the coast, their lengths are altered as they advance over the shoaling bottom, and often to such a degree as to be of considerable importance from the seaman's standpoint. This phenomenon bears so directly on the development of surf that it is discussed in more detail in relation to the latter (p. 102). It is enough here to point out that waves decreases progressively in length, as the water shoals, according to the relation-

ship explained on page 103, and illustrated in figure 21. At the same time, they first decrease slightly in height, then may increase. But they lose less than one-tenth in height at most by this initial decrease, a loss that is far outbalanced by the decrease that takes place simultaneously in their lengths, even if their heights do not increase subsequently, as may or may not happen, for the lengths have decreased by about one-third by the time the wave has reached the point where the depth of water is one-tenth as great as the initial length of the wave, and by nearly one-half when it reaches the point where the depth is only one-twentieth that great. And the steepness of the wave increases accordingly.

The lengths of the waves offshore and the angle of slope of the bottom together determine the precise distance from shore at which these stages will be reached, in the alteration of any wave, the rule being, that the longer the wave is in deep water, the farther out from the land will it begin to steepen noticeably. Waves, for example, 120 feet long, would not be noticeably steeper until they reached, say, the 2-fathom line, although their lengths would begin to decrease measurably from the time they advanced beyond, say, the 4-fathom line, however far out that might be from the land. But a 240-foot wave would have steepened noticeably when it reached the 8-fathom line, a 500-foot wave when it reached the 15-fathom line; and waves much longer than 240 feet are common.

Waves averaging about 9 seconds in period, and hence about 415 feet in length offshore, that have been recorded at South Beach, Martha's Vineyard (p. 106), should thus have begun to feel the bottom and hence to steepen when they reached the 30 to 35-fathom (180 to 210-foot) line, which lies about 40 miles out off this part of the coast. By the time they reached the 7-fathom line, they should, theoretically, have been only about three-fourths as long as they were while out in deep water, and one-half as long, but correspondingly steeper, by the time they reached the 3-fathom line. A more striking case is illustrated by a group of very heavy breakers observed on the south coast of England in winter, the lengths of which (as calculated from their periods) averaged about 1,185 feet while they were out in deep water, so that they had begun no doubt to shorten at about the 100-fathom line, on the upper part of the continental slope off the mouth of the English Channel, at least 275 miles out to seaward from the place where they were recorded on the coast (Cornish, 1910, p. 88). And additional illustrations of the same sort, if less extreme, might be cited for other parts of the world.

The southern part of the North Sea affords an interesting example of the steepening effect of a shoaling bottom on the waves in the downwind parts of partially enclosed waters of broad extent. Strong

gales from the southwest and west are common here during the winter, and the effective fetch of something like 300 miles from the English to the Danish coast (depending on the precise locality) is theoretically sufficient for a 30-mile wind to generate waves 330 to 340 feet long, or waves 115 to 125 feet long with a 20-mile wind. But the water is less than 131 feet (40 meters) deep for a distance of 60 to 70 miles out from Denmark, and less than 65 feet deep for miles, so that the waves would begin to "feel the bottom" when they still were 60 to 70 miles out from the Danish side during a 30-mile gale blowing across from the English shore. And by the time they reached the 5-fathom line, the ratios between their lengths and their heights would be only about 0.7 as great as it had been before their deformation commenced.

It is no wonder, then, that the waves of the eastern side of the North Sea are proverbially steep and dangerous for small craft in westerly gales, as are those in the western part of the English Channel also whenever storm seas are heaving into it from the open Atlantic.

But is is only while the wind is blowing strongly onshore, or following an onshore gale, that areas of shoaling bottom (even if extensive) are plagued in this way by the development of steep seas of troublesome size. The submarine shelf that fronts the southwest coast of Florida is worth citing in this connection, for while the 30 to 35-fathom contour lies 70 to 120 miles out from the land there, and even the 10-fathom contour is 25 to 40 miles out, the wind is most commonly offshore, at all seasons of the year, or blows along the shore. When it does blow onshore, it is shown on the monthly Pilot Charts as seldom stronger than about 15 nautical miles per hour (No. 3 Beaufort). Consequently, smooth seas prevail there the year round, except on rare occasions, as when a winter norther develops.

THE SIZES OF WAVES THAT ARE DEVELOPED IN SHALLOW WATER

The shapes and heights of the waves that are produced where strong winds blow across extensive stretches of shoal water are a matter of concern to the operators of small craft, both in enclosed sounds and estuaries, as well as along open coasts fronted by a gently sloping bottom during periods when strong winds blow parallel to the general trend of the shoreline. In situations of this sort, the depth of the water may directly limit the heights of waves if it is less than say 10 to 12 feet, for waves begin breaking when they grow to the point where their heights are approximately equal to the depth below undisturbed sea level.[17] But while the development of breakers usually results in the total extinction of the wave forms upon the shore, waves that grow

[17] Waves generated in shallow water in tank experiments broke where the depth was equal to 0.8 times the wave height.

in shoal water until they are about as high as the water is deep often continue to travel onward thereafter over a comparatively level bottom for considerable distances.

In this case, the intermittent spilling along the tops of their crests prevents any further increase in their heights either until their progress brings them into deepening water or until more active breaking decreases their heights to accord with the smaller depth, if their advance carries them across some still shoaler bar. Shoal water also seems to limit the sizes of waves in some other way, for often they are not as high there as the water is deep, even in situations where the wind strength and the fetch are enough for this. The distance, for example, in Pamlico Sound, N. C., is long enough from shore to shore (40 to 45 miles) for the waves produced by the strong southwesterly winds of summer to rise to 9 or 10 feet towards the end of their run, where the water is 2 to 3 feet deeper than that over a considerable area. But the local boatmen have informed us that the waves seldom, if ever, are higher there than perhaps 6 to 7 feet, no matter how strong the wind. And Pamlico Sound appears to be typical of similar situations elsewhere in this respect.

The explanation for this failure of the waves to rise higher in shallow sounds lies, we believe, in the effect that shoal water has on the lengths of the waves. Unfortunately, it is not yet known whether the relationship between wave length and depth of water follows the same curve for waves that are developed over shoal bottoms as it does for those that advance from deep water into shoal. But it is at least of the same order; i. e., waves in such situations grow more slowly in length than they would in deep water, hence they are steeper, so that they may commence to break sooner than they would otherwise. Estimations of the waves to be expected in enclosed sounds under any particular combination of wind, fetch, and depth, must await theoretical analysis of the subject, but the following rules appear to apply: (*a*) the waves in such situations will never be much higher than the water is deep and very likely will be considerably lower; (*b*) they will be steep and will break along their crests throughout the greater part of their runs, if the wind is strong.

The preceding discussion of the waves in shallow sounds applies equally to the inshore ends of the wave trains that are generated by strong winds blowing parallel to open coasts in regions where the slope of the bottom is more than usually gentle. The strong "Northers" that sometimes strike the southwest coast of Florida illustrate this, for while the fetch is long enough, theoretically, for a 30-mile wind to produce waves 18 feet high by the time they have advanced the length of the Peninsula from the offing of Apalachicola to the offing of Key West, they cannot be more than 12 feet high, anywhere along the 2-

fathom contour. And the growth of their inshore ends is still further hindered by the effects of refraction, as explained on page 155. The end result is that, while waves generated by winds blowing parallel with the coast are only a little lower near the land than they are farther out during the first stages in their development, the difference in height between the inshore and offshore sectors becomes progressively greater as they continue to advance, depending on the strength and direction of the wind, on the length of the fetch, and on the angle of slope of the bottom.

METHODS OF MEASURING WAVES

The lengths and periods of waves can be estimated from shipboard with little difficulty and with a fair degree of accuracy, if the waves are upwards of 20 feet or so long. A great number of measurements of this sort have been taken in various parts of the world.

The simplest way to measure the lengths of waves is with an old-fashioned chip log. If this is payed out over the taffrail until the chip is at the crest of one wave when the stern of the ship is on the crest of the next, the length of line outboard is equal to the length of the wave, provided the ship is running at right angles with the crests. If she is not, the angle of her course can easily be allowed for by the traverse tables that are included in every navigational handbook. Another method is to record the frequency with which the waves overtake the ship, and the time required for each crest to run her whole length from bow to stern. If, for example, it takes a wave 10 seconds to run from the stern to the bow of a vessel 300 feet long, running in the direction of the waves, and if the waves overtake the ship every 18 seconds, it means that the ship is only ten-eighteenths as long as the waves, i. e., that the length of the wave equals $\frac{300 \times 18}{10}$ or 540 feet.[18] But an allowance must be made, in this case also, if the ship is running at an angle with the waves.

Measurements, from shipboard, of the velocities of waves demand a knowledge of the speed of the ship through the water. If she is lying motionless at anchor, and the time is recorded for the crest of a wave to run along her side for a known distance, the velocity of the wave is equal to the distance divided by the time. If, for example, observers 100 feet apart were to note that it required 5 seconds for a wave crest to advance from opposite the one to opposite the other, its velocity would be 100/5 or 20 feet per second, corresponding to 11.8 knots. If the ship is running with the waves, the velocity of the latter is equal to the distance divided by the time, plus the speed of the ship. If she is running against the waves, the velocity of the latter is equal to the

[18] Adapted from Marmer, H. A., 1930, The Sea, New York, p. 182.

distance divided by the time, minus the speed of the ship. To obtain the wave velocity in feet per second, it is necessary to state the speed of the ship in the same units, a value obtained by multiplying her speed in knots by the factor 1.69. It is also necessary, when attempting to make allowance for the speed of the ship to remember that this may be greatest, temporarily, if she is sliding down the front of a wave crest that is advancing in the same direction, and least if she is meeting a crest advancing from a direction opposite to her own. Proper allowance must also be made for the ship's course if this is at an angle with the line of advance of the waves.

A single observer can calculate the velocities of waves if these are running with the ship, by paying a chip log out astern for a known distance and then recording the time interval between the instants when the chip is at the top of a crest, and when the latter reaches the ship, again with proper allowance for the speed of the ship through the water, and for her course relative to that of the waves.[20] The velocities of waves can also be calculated from their lengths, as measured above, or from their periods.

If the ship is at anchor, the time occupied in the passage of two successive crests past any fixed point on board gives the period of the wave direct. If she is under way, the simplest method of measuring the periods of the waves is to record on a stop watch the interval, in seconds, between the time when a patch of foam or other flotsam is at the top of one crest, and the time when it is at the top of the next crest—always with due regard to the likelihood that the wind may be blowing the foam ahead over the surface of the water (first proposed by Cornish, 1934, p. 38).

It is not easy to make accurate measurements of the heights of waves at sea, and rough estimates are notoriously unreliable in this respect. In most cases, the only practical method is to find some place on board from which the crests of the waves appear to be level with the horizon when the ship is in the trough of a wave and on an even keel, i. e., when she is neither pitching nor rolling at the moment. The heights of the waves are then equal to the height of the observer's eye above the water line.[21] But the heights measured in this way are only approximate at best, because it is difficult to pick a moment when the ship is actually on an even keel, and neither rising nor falling fast, and also because successive waves vary so greatly in height that it is often

[20] This method was described by the famous physicist and astronomer, D. F. J. Arago, 1857, Oeuvres complètes, Paris, vol. 9, p. 550.

[21] This simple method seems first to have been described by Arago, in the Instructions for Scientific Observations, prepared by the French Academy of Sciences for the Commanding Officer of the Corvette *La Bonite* for her voyage of exploration in 1836 and 1837 (Arago, D. F. J., 1835, Hauteur vagues, C. R. Acad. sci., Paris, vol. 1, pp. 403–404).

difficult to find an appropriate point from which to make the observations.

The heights of waves have also been estimated by the alteration that takes place in the readings of an aneroid barometer as the ship rises from trough to crest and then sinks again from crest to trough. But this method is liable to errors, the magnitude of which it is difficult to estimate; hence, it is not of much practical value under ordinary circumstances.

Waves and breakers may be most easily measured from piers with an ordinary sounding line. The lead is allowed to rest on the bottom and the line held taut, when the extent of the rise and fall of the water can then be measured on it. Or the difference in the elevation of the crests and troughs, relative to a fixed point such as the railing of the pier, may be measured by raising and lowering the lead with the surface of the water, as the latter rises and falls. Another simple method is to attach a scale of feet and inches to one of the piles of a pier, or to a pound net stake, and to read the rise and fall of the surface of the water from this, with the passage of successive crests and troughs, using a field glass or telescope if it is necessary to take the readings from a distance on the beach. Waves can also be measured from the shore by means of an anchored float which bears a vertical mast with cross arms at intervals of, say one foot, the float being observed with a transit, as the rise and fall of the water surface causes the arms to pass the cross hair in the instrument. And sighting devices of various other kinds have been devised for the purpose.

Recording meters have also been used in which a small float, rising and falling with the waves along a vertical rod, operates a pen writing on a rotating drum or on a moving tape, but these, and recording meters working on other principles, have not as yet come into general use, although they may be expected to prove useful.

Chapter 4

SEAS AND SWELLS

The characteristics of storm waves that most impress the observer are their irregularity and steepness, also their great heights in many cases, and the frequency with which their crests break, all of which may be summed up in the term "fierceness" (figs. 18 and 19). As long as waves are still in this stage of development, the combined phenomenon is known as a "sea"; one speaks of a "high sea," of a "low sea," of a "rough sea," of a "smooth sea," as the case may be. But the shapes of the waves undergo wide alterations when the wind dies down, or when the waves produced by a given wind system advance to regions outside the latter, as very commonly happens. The wave train in question is then known as a "swell," and the individual waves as individual "swells." The outstanding characteristics of a swell, as contrasted with a sea, are its low, rounded crests, the comparative smoothness of its surface contours, its great length from crest to crest, and the broad sidewise expanse of its individual crests; its gentleness, in a word, contrasted with the fierceness of the waves that composed the storm sea from which it has developed.

There is nothing astonishing to the observer in the fact that rough seas are the usual accompaniment of stormy weather, for the power of the wind forces itself on the attention of anyone who has to walk against it. But the succession of low ridges, separated one from the next by distances that may be as long as 800 to 1,000 feet, or even longer, that disturb the glassy surfaces of the open sea on a calm day is a phenomenon that must almost be seen to be believed, because the observer neither sees nor feels any immediate cause for their existence.

ALTERATION OF SEAS INTO SWELLS

The reason that a sea alters into a swell when the wind dies is that the waves then begin to loose energy, the shorter ones with the least energy becoming lower and disappearing first, so that the longer ones alone are left. At the same time, the sharp peaks so frequent during a rough sea subside; the irregularities of the surface tend to smooth out; any cross seas that may have been running upon the primary wave pattern either die down also, or are absorbed by the latter; and the remaining crests decrease progressively in height and become more rounded. The end result is that the waves tend to approach the

FIGURE 18.—A moderately high and breaking sea, as viewed from a U. S. Coast Guard Cutter. (Official U. S. Coast Guard photograph.)

FIGURE 19.—The back of the crest of a very high and breaking storm wave, viewed from a U. S. Coast Guard Cutter, as her bow is descending into the succeeding trough. (Official U. S. Coast Guard photograph.)

trochoid profile characteristic of the so-called free wave[22] of theory.

Meantime, the individual wave crests, that are seldom more than a few times as broad transversely as the wave is long during windy weather, tend to expand farther and farther sidewise, while the narrowest of them seem also to be obliterated in some way, until finally a crest that was only 500 feet or so wide, while the gale was still blowing, may expand to a breadth of 1,500 to 2,000 feet or even more. We have ourselves observed swells that were well over one-half mile wide just before they broke upon the shore. But the variations in the lengths of successive members of a given train of swells persists as the swell proceeds. Among 139 nearly consecutive breakers, for example, the periods of which were timed on the south coast of England after a heavy gale, the shortest, with a period of 10 seconds, was only 0.385 as long as the longest, with a period of 26 seconds (Cornish, 1910, p. 89).

Theories have been developed according to which the lengths of waves from crest to crest, and hence their velocities and also their periods, should increase after a sea has been transformed into a swell, contradictory though this might seem at first sight, when we remember that it is from the wind that the waves have derived their whole energy in the first place (Sverdrup, Johnson, and Fleming, 1942, p. 534). This is supported by the fact that swells of very long periods reach the Californian coast (p. 36) and also the Moroccan coast (p. 69), more frequently than would be expected from the frequency of storms in the North Pacific and the northwest Atlantic, severe enough to produce such long waves. And while it has been questioned whether the periods recorded for any particular series of breakers have been longer in any known case than might possibly have accorded with the maximum strength of the fiercest squalls during the gales that had set them running,[23] we believe the view is correct, that swells do gain in length, and in velocity and probably period as well, as they advance farther and farther from the regions of their birth.

The alteration of seas into swells is a progressive event; hence, it is never possible to pick a precise moment prior to which the waves are of the former character, and subsequent to which they are purely of

[22] A "free wave" may be defined as one that is set in motion by a sudden impulse acting once and for all and that owes its continued existence solely to the force of gravity.

[23] The offshore velocity (67.5 knots, or 78.5 statute miles per hour) deducible from the longest periods yet recorded for any group of breakers on any coast (average, 22.5 seconds for 12 successive breakers on the south coast of England) was about 11 statute miles per hour lower than the probable maximum velocity, in gusts, of the wind during the particular Atlantic gale that generated them. Wind velocities, in gusts, of 80 to 90 statute miles per hour were, in fact, recorded (by anemometer) during the preceding month over southern England, during several gusts, with a maximum of 101 miles per hour, briefly. (Cornish, 1910, pp. 118–120, and 1934, pp. 11–14.) But it is a question whether squalls as violent as these last long enough, or extend over areas large enough, for the generation of waves as long as those of the group of swells in question. This matter of squalls is also discussed on pages 20 and 26.

the latter. But the transformation is often very rapid when the wind dies down, as every mariner knows. On a recent occasion, we noted that a low, but rough, sea about 2 to 3 feet high had become transformed into a swell, though still nearly as complex in pattern, during a period of about 2 hours, as the breeze slackened; the smaller wavelets were almost entirely absorbed into the higher and longer ones during the ensuing half hour, by which time the wind had entirely died out. And the alteration in character from sea to swell may be as rapid for larger waves as for small ones if the wind falls flat, though the incorporation of the younger waves into the older and longer ones on which they are running requires a longer time when the parent seas are large than when they are small.

Very few observations have been made as to how rapidly the height of a swell decreases in calm weather. In one published instance, the heights of swells running from the West Wind Belt in the southern Indian Ocean were described as decreasing by about one-half in a distance of 350 miles. And we have ourselves seen a small swell of about 2 feet fall to about 3 inches in a little less than one hour during a flat calm.

THE DIRECTIONS OF SWELLS

The directions in which swells advance are reminiscent not of the winds at the time of observation, but either of winds that blew previously or of wind systems at a distance. Consequently, the swell that is encountered at sea on any given occasion may be coming with the wind; it may run against the wind (if the latter is not strong enough to have flattened the waves down); it may run at any angle with the wind; or it may run ahead of the wind so that a ship in the path of an oncoming storm may find herself plunging into swells so heavy that she takes water over the bow, even if the weather is perfectly calm for the time being. But the direction of advance of a swell, if reversed, leads back toward the place where its parent waves were produced, because waves once set in motion continue to progress in their original direction for as long as they continue in deep water, regardless of any subsequent changes in the direction of the wind (fig. 20). If the swell continues to come from the same direction, it may be assumed that the storm area as a whole is either advancing directly toward the observer, that it is receding directly away from him, or that it is stationary for the time being. If, however, the swells are coming from a storm that is passing by, their direction of advance will change as illustrated in figure 20.

Thus the sudden development of a heavy swell at sea, or of a surf upon the coast, may give warning in this way of the approach of a

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storm; and the length of the warning will depend on the rate at which the waves outstrip the storm. Swells, for example, with an average period of 10 seconds, coming from a tropical hurricane 600 miles off shore would reach the coast about 24 hours in advance of the storm itself, if the latter were advancing at the rate of 10 knots. But 12-second swells would precede the storm by about 9 hours only, if it were advancing at 15 knots. And we must caution the reader that the approach of a hurricane is not always heralded in this way by swells coming in advance of it.

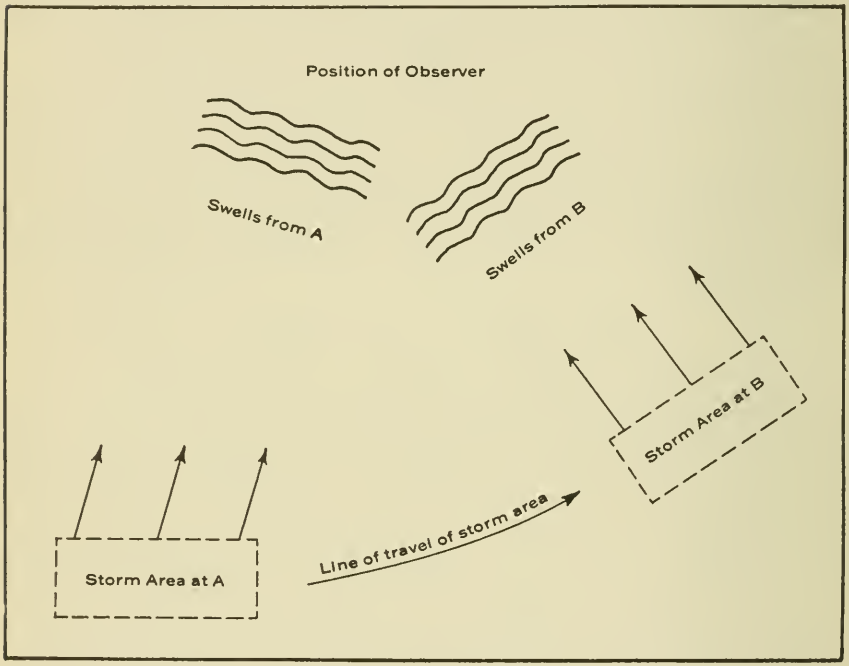

FIGURE 20.—Diagram to show the changes in directions from which swells come, with the advance of the storm center that produces them.

The direction from which swells come, from hour to hour, may also give some clue to the direction in which the storm center is moving. But the application of this principle is complicated by the fact that the directions of the waves within tropical hurricanes may diverge considerably from the direction of the wind there, as described on page 40, because the latter circles so sharply along the atmospheric pressure gradients in storms of this type, to the left (counterclockwise) in the Northern Hemisphere and to the right (clockwise) in the Southern Hemisphere, according to the "Law of Storms," with which every navigator is familiar. And while the direction of the swell, in reverse, as observed out in deep water, points toward the storm area,

it may no longer do so by the time the swells reach the coast, because of the refraction to which they are subject as they advance over a shoaling bottom (p. 155).

Perhaps it is hardly necessary to caution the reader that the familiar phenomenon of a swell reaching the coast ahead of a storm has no bearing on the question whether the velocities of the swells are higher than that of their parent seas and winds, but simply means that the swells often outrun the storm centers, or wind systems as a whole, even when these are moving in the same direction. In fact, swells often reach the coast from storms that pass by offshore, altogether.

THE PERSISTENCE OF SWELLS

The identification of the regions from which swells originated, through the study of synoptic weather maps, combined with vessels' log books, has proven in many instances that swells may run for hundreds, or even for thousands, of miles, unless they are beaten down by contrary winds. Thus, a swell from the northwest, originating from severe gales in the Gulf Stream region south of the Newfoundland Banks, has been reported not only in the Trade Wind Belt at a distance of 1,500 miles, but even within 270 sea miles of the coast of Sierre Leone, i. e., at a distance of at least 2,500 miles from its birthplace. Very heavy swells have, again, been experienced on the south coast of England at a distance of at least 1,680 sea miles from the storm center that almost certainly gave them birth, while in December 1880 the whole eastern half of the northeast Atlantic experienced a swell, spreading from an area west of the Azores, following winds of hurricane force that had blown there 2 days before (Krümmel, 1911, pp. 87, 88, fig. 21). It has also been known for many years that swells from the winter gales of the West Wind Belts of high latitudes, north and south, are common in the equatorial belt of the Atlantic. Indeed, they reach the coast of Morocco so regularly from barometric depressions between Ireland and Iceland, some 1,600 miles away, that swells of 3 feet (1 meter) or higher were recorded at Casablanca and at Rabat on every day when observations were made, from January 1943 to April 1945. Their average heights ranged from a little more than 3 feet (1.2 to 1.3 meters) during July and August to about 10 feet (3.1 to 3.2 meters) in January, with a maximum of about 26 feet (recorded for March),[24] while their recorded periods ranged up to 17 seconds as they approach the shore. And the French Department of Public Works of the Moroccan Protectorate of Rabat has found it possible to predict their arrival about 70 percent of the time.[25] They

[24] Observations by Institut Scientifique Cherifien, French Morocco, received through Commander C. J. Fish, U. S. N. R.

[25] Cited from Marmer, H. A., 1930, The Sea, New York, p. 189.

often cause a violent surf even on the islands of Ascension and of St. Helena in the South Atlantic (in latitudes of about 8° S. and 15° S., respectively) from December to April; and, in the same way, heavy swells from the storms of the Westerlies in high latitudes of the South Pacific run to the island shores of the Paumotos Group, so that they may be expected finally to intermingle with the swells that are generated by the Southeast Trades.

A swell would eventually be extinguished by the internal friction of the water and by the resistance of the air that it displaces in its advance, if the ocean were of unlimited extent. But this friction is so small that swells actually tend to run until they strike some coastline, or until they are beaten down by an opposing wind, which may happen so rapidly that a fresh trade wind has frequently been seen wholly to smooth out a moderate swell under the eye of an observer. And the effect of floating ice is still more spectacular in this regard, as described below (p. 147).

FORECASTING SEA AND SWELL

The prediction of the swell and state of the sea a day or more in advance can be accomplished by the proper use of the relationships summarized in tables 4 and 5, provided sufficient data on wind conditions are available. The details of the operations necessary to make a forecast are given in *Wind waves and swell; principles in forecasting* published by the United States Hydrographic Office.[1] Such predictions have been found very useful during wartime unloading operations off open beaches, as during the allied invasion of Europe. For practical purposes, it is important to know the size of the largest waves rather than merely the mean of the entire set, and the predictions give approximately the mean of the highest third of the waves.

[1] Superseded by H. O. Pub. No. 604, *Techniques for Forecasting Wind Waves and Swell.*

Chapter 5

THE FREQUENCY OF HIGH AND LOW SEAS AND SWELLS IN DIFFERENT REGIONS

It is not possible, as yet, to picture the average condition of sea or swell for any part of the world in more than a very rough way, for while great numbers of reports of the heights of waves have been received at the Hydrographic Offices of the maritime nations, these have not only been concentrated chiefly along the more travelled routes, but the great majority have been rough estimates only. A criticism, equally serious from the mariner's standpoint, is that the reports available for this study yield no information whatever as to the frequency with which the sea runs higher than 20 feet, as they often do in the Westerlies of both hemispheres during the stormy season, as well as under the southwest monsoon in the North Indian Ocean.

The charts presented here (pls. I to XXIV), with the accompanying discussion, are based upon information received and analysed at the United States Navy Hydrographic Office chiefly for the period from 1932 to 1940. The relative frequencies (stated as percentages of all reports received) with which the sea and swell was reported as "calm," as "low," as "medium," and as "high" were calculated for each 5° square, or similar area, and it is from these percentages that the contours were laid down on plates I through XXIV. The categories are based on wave heights which are different for sea and for swell. "Low," "medium," and "high" seas indicate waves of 1 to 3 feet, 3 to 8 feet, and 8 feet or higher, respectively, whereas the same categories for swell indicate waves of 1 to 6 feet, 6 to 12 feet, and 12 feet or higher. This distinction between the measurement of sea and swell complicates any comparison between the relative frequencies of low waves of the two classes, but it is still possible to compare high waves in a rough way.

Failure to mention "calm" water more than casually in the following discussion is deliberate, due to the very strong probability that a very old and hence very low swell may be overlooked, and that a sea only a few inches high may be reported as "calm." Actually, it is only when there is no wind at all that there is no sea at all. Likewise, it is unlikely that any considerable part of the open ocean is ever wholly free from a swell, though the latter is often so low and so long that its presence is made visible only if it runs into shoaling water. For these

reasons, the category "low," as used below and on the charts, includes "calm" unless otherwise noted.

The value of presentations of this sort depends chiefly on how far the data on which they are based can be regarded as representative. The percentages have been taken into account only for such of the 5° squares as were the subject of at least 10 reports for the time in question; this minimal number is so small that the contours as laid down on the charts are offered only as the roughest of approximations, except perhaps along the chief steamer lanes, where the picture is more dependable. Where fewer than 10 reports were available for a 5° square, the area has been left untinted.

The features of seas and swells of primary and secondary importance to the mariner are the frequencies with which these run high and low, respectively, in one part of the ocean or another at different times of the year. It has seemed sufficient to limit the comparison to winter and summer, these being the seasons when the weather is either at its stormiest or the reverse over most parts of the oceans. In the following discussion, "summer" and "winter" refer to those seasons in the Northern Hemisphere.

Paucity of data has made it necessary to base each of the seasonal charts for the Indian Ocean, for the South Pacific, and for the South Atlantic on percentages derived from the total observations for two months (July and August representing summer conditions and January and February, winter). Winter conditions in the North Atlantic are also shown by combining the data for January and February, since the percentages derived in this way appear to yield a more representative winter picture for that area. Winter conditions in the North Pacific are based on data for February alone, and summer conditions for both the North Pacific and the North Atlantic are drawn up from August reports only.

NORTH ATLANTIC

Summer.—The northern part of the North Atlantic is least often rough in July and August for the very obvious reason that winds of gale force (force 6 to 8 Beaufort or stronger) are least frequent then, even in high latitudes. It is only to the northward of the general latitudes of southern Newfoundland, for example, and of southern Britain—locally, too, off the coast of northwest Africa—that seas higher than 8 feet have been reported as often, even, as 10 percent of the time for August; while seas of even that moderate height, in frequency greater than 20 percent, have been reported only for the waters between southern Greenland and Scotland.

Elsewhere throughout the North Atlantic the seas of late summer may be characterized as the least often high and as the most often low

in the Equatorial Belt on the African side; considerably less often low along the Northeast Trades; more commonly low, again, in the latitudes of the Variables, as well as along the northeast coast of the United States; but less and less often so to the northward. And the wave pattern, while somewhat skewed, is nearly enough latitudinal for the following table to illustrate the south-to-north gradation in the prevailing heights of the sea, at least in a rough way.

TABLE 19.—*Maximum, minimum, and mean percentages of low, medium, and high seas in 5° squares for different latitudinal belts of the North Atlantic in August*

North latitude	Low seas			Medium seas			High seas		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0–10	81	17	49	74	19	49	9	0	2–3
10–20	75	15	46	70	25	50	19	0	4–5
20–30	82	17	49	78	19	48	14	0	3–4
30–40	78	29	58	64	19	40	7	0	2–3
40–50	68	30	48	61	30	45	13	2	7
50–60	55	14	32	58	29	47	36	9	21

The contours for high seas and for low, in different frequencies, as laid down in plates I and II, are self explanatory in most respects. Attention should, however, be called to the prevailing smoothness of the sea along the northeast bulge of South America in the Doldrum Belt between the southern boundary of the Northeast Trades and the northern boundary of the Southeast Trades, on the one side of the ocean, and along the coast of equatorial West Africa from Cape Palmas to the Gulf of Guinea on the opposite side, i. e., between the Southeast Trades and the land.

The increasing frequency with which seas higher than 3 feet ("medium" according to the code adopted), and even higher than 8 feet (2 to 9 percent), are encountered, running out from the African coast into the Southeast Trades (which reach north of the equator in summer), is in line with common experience.

The situation is similar along the axis of the Northeast Trades, from the African coast between latitudes 20° and 35° N., right across to the northern part of the Lesser Antillean chain, where the sea has been reported in August as "medium" for about 65 percent of the time, which accords with an average strength of about 14 to 16 knots for the Trades, where best developed. In fact, the seas are seemingly more uniform in height along this belt than they are anywhere else in the North Atlantic at this season. Even so, the reports for August have shown a considerable gradation from east to west along the Trades, the sea being somewhat more often high (10 to 14 percent) on the African side than to the westward and in the Caribbean (0 to 8 per-

cent). We cannot offer any explanation for this contrast, since gales are not reported any more often near the African coast at this season than they are farther to the westward; neither do the Trades commonly blow any more strongly there, nor more constantly in the one direction.

The seas average somewhat lower toward either boundary of the Northeast Trades than along the axis of the latter, as might be expected from the character of the wind; this is especially true along the northern Bahamas and toward the coast of southern Florida, where the sea has been described as "low" in 75 to 80 percent of the August reports, and only very seldom as "high". And this applies equally to the Gulf of Mexico (seas 70 to 80 percent low, 0 to 1 percent high). The Gulf is in fact as smooth as, or perhaps even smoother than any subdivision of the open Atlantic of equal extent at this season.

The reader might reasonably object, here, that neither the foregoing account nor the charts (pls. I and II) give any hint of the fact that high and very dangerous seas do accompany the tropical hurricanes that occur from time to time at this season, some of them crossing the Caribbean and the Gulf of Mexico, but others skirting the West Indies, Bahamas, and Florida, either to spend their force inland, or to run parallel to the coast of the United States northward and northeastward. The reason they do not more evidently influence the frequency with which "high" seas are reported, is that really severe storms of this nature are rather unusual events, even in the regions where they occur the most commonly in the month in question. Thus the total number of storms of this kind, of hurricane force, that were recorded for August from 1887 to 1936 was only 51 (Tannehill, 1938, p. 113), or about 1 per year, corresponding to which the percentage of severe gales is shown on the Pilot Chart for August as only 0 to 1 for the region in question.[26]

The great frequency with which the seas are low (more than 40 percent) and the infrequent occurrence of high seas (0 to 7 percent) are the outstanding features of the wave pattern of summer along the belt of variable winds in the western half of the ocean, between the northern boundary of the Trades and about latitude 40° N.

The scarcity of high seas anywhere along the United States coast as far north as the Grand Banks of Newfoundland (0 to 5 percent) in summer is due to the fact that onshore winds, or longshore winds, strong enough and with a fetch long enough to generate waves of any considerable size are not usual there at this time of year. And it is this prevailing smoothness of the sea, combined with the great number of good harbors, that makes our northeastern coast the summer

[26] The tracks of many of these cyclonic storms are laid down on the U. S. Hydrographic Office Pilot Charts for August and for September, as well as for other months.

playground that it is for innumerable small-boat sailors. In fact, there is probably no better or safer cruising ground for small yachts anywhere in the world than between New York and Nova Scotia, which would be equally true to the southward were safe anchorages as numerous there and located as close together. The contrast in this respect between the east coast of the United States and the west coast of Europe is considerable, for while the ocean is at its smoothest there, too, in summer, the sea runs high for as much as 12 or 14 percent of the time even then, not only along western Ireland and western Scotland in the north, but also along the Iberian Peninsula to the southward, and 5 to 6 percent of the time in the intervening waters of the Bay of Biscay, as well as off southern Britain. And there is a corresponding contrast in the frequency with which the sea is reported as less than 2 to 3 feet high along the United States coast (about 60 to 81 percent), on the one hand, and along the coast of western Europe from Spain to Scotland (about 33 to 55 percent), on the other. In fact, one must sail northward as far as the coast of Newfoundland to find sea conditions on the American side of the Atlantic comparable to those along Spain and Portugal, or in British waters. Yachtsmen, in particular, are well acquainted with this difference in the prevailing state of the sea in the two sides of the North Atlantic in midlatitudes, and so are marine architects, for racing craft must be designed for maximum speed in rougher water in Europe than in the United States.

The Gulf of St. Lawrence is of interest in this connection, for while the sea is reported "low" almost as often there (73 percent) as it is even off the northeast coast of South America, seas higher than 8 feet are also comparatively frequent there (9 percent); this agrees with common report (with our own experiences, too) that the Gulf in summer is either pleasantly smooth or decidedly rough.

The frequency distribution for swells of different heights over the North Atlantic Ocean in summer recalls that for seas. It is only to the northward of about latitude 50° N. that swells higher than 12 feet are reported for August with a frequency as great as 20 percent, while the most extensive area where the swell is described as "low" in more than 60 percent of the reports for that month is along the belt of variable winds in midlatitudes. But the differences in detail between the distribution of swells and of seas are enough to call for some discussion. Thus, a high swell is reported with 9 to 20 percent frequency in August from Newfoundland right across the Atlantic to the coast of Europe (Scotland to southern Spain), where a high sea is decidedly less common; also thence southward in a continuous tongue along the coast of Africa about to the latitude of Cape Verde, where high seas in equal frequency are confined to a much less extensive pool between the vicinity of the Canary Islands and the vicinity of Cape Blanco.

High swells similarly average about twice as frequent (about 7 percent) as high seas do (about 3 percent) for the North Atlantic in August from latitude 40° N. southward, the contrast in this respect being especially interesting in the downwind parts of the two Trade Belts off South America, where a high swell has been reported locally in August with frequency as high as 19 to 23 percent, but high seas with only 9 percent at most.

On the other hand, the mid-latitudinal belt where the waves are reported as "low" more than half the time in summer is much more extensive for swells than for seas (cf. contours for 60 percent low, pls. II and IV), while the swell is also more often low along the West African coast between the offings of Cape Verde and of Cape Palmas during that month (60 to 84 percent) than the sea is (42 to 62 percent). The greater frequency with which the category "low" is reported for swells than for seas is probably due to the fact that it includes a wider range of heights for the first of these classes of waves than for the second, as explained on page 71. But it is likely that the discrepancies between the frequency distributions for high seas and for high swells chiefly reflect the fact that, while the former are the direct product of whatever wind may be blowing at the time, the swell that is encountered on any given occasion is likely to be the cumulative product of seas generated by stronger winds alternating with weaker winds, or even with calms.

We may also point out that high swells are perhaps a better index to the effects of hurricanes in the western side of the Atlantic than high seas are, to judge from the fact that the former are reported decidedly more often (6 to 12 percent) than the latter (1 to 3 percent) to the north of the Virgin Islands, as well as in Bahaman waters; high swells are also more frequent (6 to 7 percent) than high seas (1 to 2 percent) out from the coasts of the Carolinas.

Closer analysis of the local differences between the frequency distributions of summer swells and seas of different heights over the North Atlantic would require a much more detailed comparison between the waves and the character of the wind, and especially with the frequency of gales, than we have been in a position to undertake.

The state of the swell in August may be summarized as follows for enclosed seas on the western side of the Atlantic:

a. Gulf of St. Lawrence.—Swell lower than 5 to 6 feet for more than three-fourths of the time (82 percent), and very seldom high (0 percent), as might be expected from the fact that the maximum effective fetch within the Gulf is not more than about 180 miles, no matter what the direction of the wind may be.

b. Gulf of Mexico.—Swells low over the entire area of the Gulf for at least 80 percent of the time, and for more than 90 percent of the

time along both its northeastern shore and in its southern side; swells are high for only 0 to 5 percent of the time.

c. Caribbean.—Swells low only about 56 percent of the time on the average with 84 percent as a maximum, thus considerably less often than in the Gulf of Mexico. Although high swells are no more frequent along the south coast of Cuba (3 percent), or in the shelter of the Antillean chain (1 to 5 percent), where the effective fetch for the Trade Winds is negligible, than they are in the Gulf of Mexico, they are reported with 8 to 12 percent frequency by the time the waves generated by the Trades have reached the downwind parts of the Caribbean, off the coasts of Colombia, Costa Rica, and Nicaragua, where the Trades have an effective fetch of something like 350 to 375 miles.

The failure of high swells to develop more often than they do in the northern side of the Caribbean, in spite of the tendency for the tropical cyclones that cross the latter to follow this general track, reflects the rarity of such storms there. The pilot chart shows the tracks of 10 only, as following this particular route, for the month of August, over the period from 1901 to 1940.

Winter.—The increasingly stormy weather of autumn in high latitudes, with its continuance through the winter, results, as one might expect, in an increase in the average frequency of high seas to 50 to 60 percent and more between Newfoundland, Greenland, and the coasts of northern Europe. This stormyness also causes so wide an expansion, from summer to late winter, in the confines of the region where high seas are encountered for more than a very small part of the time that more than 20 percent of the reports for January and February combined have classed the sea as "high" throughout the whole of the North Atlantic down to latitudes 30° to 35° N., excepting only along the coasts of southern Spain and of northwest Africa in the one side, and along the northeastern United States in the other.

An interesting illustration of the dependence of the height of the sea on the strength of the wind is also to be seen in the fact that the boundaries of the tonguelike extension, southward and westward in midocean, of the area where a high sea is reported more than 40 percent of the time, as shown on plate V, corresponds in general with the limits of the region where gales occur in February with frequency greater than 15 percent, as outlined on the Pilot Chart.

Another point of interest is that, while in summer the sea is oftener high along the coasts of western Europe than along the eastern United States at corresponding latitudes (p. 75), there is little difference in this respect during the stormy half of the year between the western side of the Atlantic and the eastern. In fact, the sea has been reported "high" rather more often from Nova Scotia to the Grand Banks

of Newfoundland at that time of year (31 to 39 percent) than for the Bay of Biscay, off the mouth of the English Channel, or along the west coast of Ireland (24 to 31 percent).

We would leave the reader with only a very pale picture of the actual fierceness of the sea that ships often encounter in high latitudes of the North Atlantic, during winter gales, if we were to stop here, for no one, we fancy, who has made many winter crossings during the stormy season would class an 8- or 9-foot sea as a high one at that time for that part of the ocean. Actually, waves of 20 feet or higher have been reported by sailing ships during 13 percent of the time between Newfoundland and England for the year as a whole, for which no doubt the storms of winter are chiefly responsible (p. 77). And waves more than 40 feet high have been reliably reported, not only along this belt where the Westerlies rule, but even as far south as the vicinity of the Azores in the eastern side of the Atlantic, during winter gales of unusual severity, as described above. The data at hand do not afford any further information in this regard, except that it is certainly unusual for the sea to rise much higher than 15 feet or so anywhere in the western side of the Atlantic south of Newfoundland, unless during exceptionally severe gales. And we might remind the reader that tropical cyclones of hurricane force have never been known to develop in the Atlantic in winter. (See Tannehill, 1938, p. 222.)

Corresponding to the general increase in the frequency of high seas in winter, the area in mid-latitudes where a low sea is reported with frequency as great as 40 percent in August (pl. II) contracts between August and January to February, to a much narrower belt north of the Trades between the latitudes of northern Florida and of the northern Antilles (pl. VI); during these months, too, it is less usual to meet a very low sea even there (40 to 54 percent) than it is at the end of the summer (62 to 81 percent).

A still more striking alteration of this same order also takes place from summer to winter in the western side of the North Atlantic, along the southern margin of the Trade Wind Belt off South America, where the frequency of seas smaller than 2 or 3 feet falls from 40 to 80 percent in August to only 10 to 35 percent at the end of the winter; this alteration, no doubt, reflects the strengthening through the autumn of the Northeast Trade Wind to a winter average of 14 to 16 knots, or even higher. But the prevailing height of the sea does not alter much from summer to winter in the eastern part of the Trade Belt, between the Cape Verdes, the Canaries, Madeira, and the coast of Africa, where the average strength of the wind does not change much from the one season to the other (average about 12 to 14 knots

from December through February as well as from June through August). And the sea ranges low for nearly or quite two-thirds of the time by the end of the winter, not only along equatorial West Africa as is the case in summer, but westward thence, as well, right across to the longitude of eastern Brazil (See the contours for "low seas" with 60 percent frequency, pls. II and VI) following on the autumnal migration southward of the Southeast Trades.

We have only one report of the state of the sea in the Gulf of St. Lawrence for January, none for February. And in any case, there is so much drift ice in the Gulf toward the end of the winter that scattered data would be of little significance there.

High seas are somewhat more frequent in the Caribbean during January and February (2 to 13 percent) than in August (0 to 11 percent), corresponding to the fact that the Trades average somewhat stronger there in winter than they do in summer, though the sea is reported "low" about as frequently there at the one season as at the other (22 to 51 percent in summer, 21 to 38 percent in winter). The sea, too, is usually much the smoothest close under the shelter of the Lesser Antilles, of the Virgin Islands, of Puerto Rico, of Hispaniola, of Jamaica, and of Cuba, and the roughest off the coasts of Colombia, of Costa Rica, and of Nicaragua, in winter as well as summer, which is to be expected, since the Trades are the governing winds over the Caribbean the year round. The seasonal succession is similar to this in the Gulf of Mexico, where the stronger winds of winter, with occasional gales of moderate strength, generate high seas during 2 to 7 percent of the time and most often in the general vicinity of Tampico, with the corollary result that one is considerably less apt to find the sea low there during the winter (45 to 68 percent) than at the end of the summer (70 to 91 percent).

An interesting corollary of the stormy weather of winter is that the swell runs high considerably more often at that season than the sea does, wherever a high sea is a common event. The most striking illustration of this rule is to the northward, as illustrated by the much wider areas enclosed by the successive contours for high swells (pl. VII) than by the corresponding contours for high seas (pl. V).

This predominance of high swells over high seas in the stormier latitudes of the North Atlantic probably results from the fact that the swells resulting from the seas raised by one storm are followed so soon by the swells from the next, that the surface of the ocean is never free from them. Similarly, the swell runs high nearly twice as often in winter (20 to 30 percent) as the sea does (13 to 18 percent) in the downwind part of the Northeast Trades, no doubt because seas are so soon transformed into swells, if the wind slackens temporarily.

The increasing frequency through the autumn of high seas over the northern part of the North Atlantic is further reflected in the fact that most of the area of the latter is disturbed by a swell of 12 feet or higher for more than one-tenth of the time by the last part of the winter. The only exceptions are along the Lesser Antilles, the Bahamas, and northern Cuba in the west, also the subequatorial belt in the east, from equatorial West Africa out to the longitude of eastern Brazil, where a high swell, like a high sea, has not been reported at all in January and February for some of the 5° squares, nor in frequencies greater than 6 or 7 percent for any of the others. To the northward, indeed, of the Northeast Trades, it is only off the coasts of Florida, Bahamas, and Cuba that the swell has been reported "low" or altogther absent for as much as 60 percent of the time in late winter; whereas in August this applies not only to the entire western side of the North Atlantic, west of the longitude of Newfoundland, but also to an extensive area as well in midlatitudes in midocean (pl. IV).

A longitudinal contrast, of practical interest in the state of the swells of winter, is that these are considerably less often high along the coast of the northeastern United States and off the coasts of Europe and of northwest Africa than they are in midocean, as is illustrated by table 20.

High swells are somewhat more common in the Gulf of Mexico in winter (4 to 9 percent) than at the end of the summer (0 to 5 percent) ; likewise, they are considerably more common throughout the Caribbean as a whole, much as high seas are (p. 79), and with similar gradation, with frequencies from about 5 percent under the immediate shelter of the Antilles in the east but 11 to 20 percent along the coasts of Colombia and of Nicaragua in the west.

TABLE 20.—*Ranges of percentage frequencies of high swells in unit areas of the North Atlantic in January and February, to show the contrast between the frequency of high swells within approximately 500 miles of the American and European coasts and that in midocean*

North latitude	Off coast of America	Midocean longitude 30°–40° N.	Off coasts of Europe and Africa
	Percent	*Percent*	*Percent*
50°–40°	10–36	52–63	31–46
40°–30°	10–23	36–50	25–41
30°–20°	4–17	25–37	11–18

SOUTH ATLANTIC

Available data suggest that a really high sea is about as common in high latitudes of the one hemisphere as of the other during the stormy

season, for the frequency with which waves of 20 feet and higher have been reported for the year as a whole is very nearly the same for the South Atlantic, in the latitude of southern Argentina (12 percent), as in the North Atlantic between Newfoundland and England (13 percent. See table 8, p. 21.)

On the other hand, the seasonal expansion and contraction of the limits of the area where a high sea is commonly encountered in the Southern Hemisphere is the reverse of that in the Northern, as illustrated by the fact that while, in the latter, it is in January and February that the contour line for high seas in 10 percent frequency approaches nearest to the equator, it is in August that this happens in the South Atlantic. This difference was of course to be expected from the fact that the northern winter is the stormy season in the Northern Hemisphere, whereas it is stormiest in the Southern Hemisphere during the northern summer. Correspondingly, it is during the northern winter, when the high and mid-latitudes of the North Atlantic are the most often troubled with high seas, that the sea is the least often rough in the corresponding belt of the South Atlantic.

A heavy swell, too, is reported considerably more often throughout all but the subequatorial region of the South Atlantic during the northern summer than it is in the North Atlantic, for this same reason, the opposite being true in northern winter. This again is consistent with the differences in seasons in the two hemispheres. During the stormy half of the year, too (northern summer in this case), a heavy swell has been reported generally throughout low and mid-latitudes of the South Atlantic considerably more often than a high sea has, much as is true of the North Atlantic in the northern winter, and no doubt for similar reasons (p. 78).

Although the number of reports received from the South Atlantic is small except along the two coasts, they are enough to show that the frequency distribution of seas of different heights there in the northern summer is roughly a mirror picture of the sea pattern of the North Atlantic; i. e., while a heavy sea is the most common in high latitudes and least so in low, in both oceans, the area where the sea is low for more than half the time extends farthest from the equator in the eastern side in the Southern Hemisphere, but in the western side in the Northern. In northern winter, high seas, and high swells as well, are considerably more common off the coast of Africa at corresponding latitudes, to the southward of about 20° S., than off the coast of South America, which is true of high swells in the northern summer as well. (See tables 21 and 22.)

TABLE 21.—*Avcrage percentage frequencies of low and high seas and swells in the South Atlantic within approximately 300 miles of the coasts of South America and of Africa in July and August*

South latitude	Seas				Swells			
	Off South America		Off Africa		Off South America		Off Africa	
	Low	High	Low	High	Low	High	Low	High
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0°–10°	22	8	79	0	41	14	70	2
10°–20°	33	8	53	4	43	15	50	15
20°–30°	41	10	43	13	49	17	40	23
30°–35°	35	15	39	13	48	19	30	44

TABLE 22.—*Average percentage frequencies of low and high seas and swells in the South Atlantic within approximately 300 miles of the coasts of South America and of Africa in January and February*

South latitude	Seas				Swells			
	Off South America		Off Africa		Off South America		Off Africa	
	Low	High	Low	High	Low	High	Low	High
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0°–10°	53	1	59	0	66	5	61	5
10°–20°	56	1	59	0	77	1	59	9
20°–30°	46	7	28	12	61	7	37	20
30°–35°	40	5	29	16	52	13	28	35

NORTH PACIFIC

Summer.—The available data vary even more widely in number from one unit area to the next for the Pacific than for the Atlantic, and they are less numerous for most of the squares, especially along the equatorial belt. There are enough, however, to show that the regional variation in the relative frequency with which seas of different heights are encountered in summer is fundamentally the same for the one ocean as for the other, as is to be expected from the fact that the wind systems are essentially similar over the two. Thus, it is only to the north of about latitude 50° N. that high seas are reported in August in the Pacific as often as 20 percent of the time. In the Pacific, too, as in the Atlantic, northward from about latitude 35° N., high seas are not only considerably more common near the coast in the east, at that time of year, than in the west, but they are reported about as frequently from southern Alaska to the offing of Los Angeles (5 to 17 percent), as from Ireland southward along Europe and northwest Africa to the vicinity of Cape Verde. Also high seas are about as frequent along the Pacific shores of Japan and of the Kuriles (2 to 7 percent), as along the eastern United States, north of Florida, or along Nova Scotia.

The area, however, where a high sea has been regularly reported in August during more than 10 percent of the time extends something like 1,200 miles farther southward in midocean in the Pacific (to about latitude 25° N.) than in the Atlantic (to about 45° or 46° N. only; cf. pl. IX with pl. I). A high sea is also reported about four times as often on the average (8 or 9 percent) from southern Japan southward, past the northern Philippines to the offing of Mindanao in the open Pacific, as well as locally in the northern part of the South China Sea, than it is along the Atlantic seaboard of North America as a whole from Cape Hatteras southward, in the West Indies, in the Gulf of Mexico, or in the Caribbean (average about 1 or 2 percent). This difference between the two oceans may be partially due to the fact that the prevailing winds of summer are somewhat weaker along the southeastern United States and in the Gulf of Mexico at that season than in the western side of the Pacific at corresponding latitudes, where they average 12 to 14 knots. But it is also likely that the dangerous waves raised by tropical hurricanes have been included more often in the reports of the state of the sea in the western tropical Pacific for the late summer than they have in the Atlantic, for the typhoon season is not only at its height then, but dangerous storms of this nature cross the East and South China Seas much more often than they do the western tropical Atlantic, the Caribbean, or the Gulf of Mexico. The Pilot Charts for August, for example, show the tracks of 169 for that general part of the Pacific for the 25-year period from 1921 to 1945, but only 36 for the western tropical Atlantic for the 39-year period from 1901 to 1940.

Neither are there any apparent counterparts in the North Atlantic to the "pools," so to speak, in mid-Pacific, the one extending southeasterly from the Hawaiian Islands, the other lying farther southeastward in the equatorial belt, where high seas are reported in summer in frequency as great as 10 percent. No doubt the Northeast Trades are responsible in the first case, for it is about here that they average their strongest in summer, and the Southeast Trades for the second.

On the other hand, a high sea is reported considerably less often along the coasts of Central America and of Lower California in the eastern tropical Pacific in August (0 to 2 percent) than it is in the corresponding latitudinal belt of the eastern Atlantic from Gibraltar to Cape Verde (7 to 14 percent). At the same time, what may be named the "east-tropical smooth" (outlined on the charts by the contours for 60 percent low) extends some 1,500 miles farther northward in the eastern side of the Pacific, where it reaches to southern California, than in the eastern side of the Atlantic. The smoothness of the sea in this part of the Pacific no doubt reflects the fact that the inshore

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boundary of the Trade Wind Belt is separated from the coasts of southern and of Lower California by a belt some 300 miles wide at its narrowest, with the coasts of Central America fronting on the Doldrum Belt, where the winds are not only variable, but as a rule weak. Available information for summer also makes it likely that a smooth sea is equally characteristic along the equatorial belt in the western half of the Pacific, though the reports received thence were not numerous enough to have much statistical value. And more frequest reports of low seas westward along the Northeast Trades from about the longitude of Wake Island and of the Marshalls, than eastward, accord with the wind distribution at this season. It is doubtful, however, whether there is any clear parallel in the North Pacific to the smooth belt along the belt of Variables that is so conspicuous a feature of the sea pattern of summer in the North Atlantic (p. 74). Perhaps as good an illustration as any of the contrast between the summer seas of the two oceans in this last respect, is that the general August average between latitudes 25° and 35° N. is about 52 percent low and about 8 percent high for the North Pacific west of the longitude of western Alaska, but about 67 percent low and only 0 to 4 percent high for the North Atlantic west of about longitude 35° W.

Ten of the 19 reports received from the southern part of the Sea of Okhotsk for July and August (we have no information from its northern part) described the sea as "low," none of them as "high," which is in agreement with the fact that gales of force 8 or stronger are so uncommon, at that time of year, over the waters between Kamchatka and the Asiatic coast that their percentage is shown as zero there on the Pilot Chart for August.

The summer seas run low rather more commonly in the Sea of Japan (41 to 80 percent according to locality) than in the Sea of Okhotsk, nor is a high sea reported at all there in August and only occasionally (0 to 5 percent) in July. And the state of the sea is much the same as this in the Yellow Sea. It rises high rather more often, however, in summer in the South China Sea (0 to 14 percent frequency), due to the gales that sometimes blow there and to the occasional typhoons that cross its northern half; the Hydrographic Office Pilot Chart for August gives frequencies of 1 to 4 percent for gales for the South China Sea as a whole and shows the tracks of 4 typhoons crossing its northeastern part. But the sea has been classed as "low" in 94 to 100 percent of the August reports from the waters between the southern Philippines, Borneo, and Celebes, nor do they mention a high sea at all, ordinary gales and typhoons alike being unknown there.

In a general way, the summer swell is most often high in the parts of the North Pacific where the sea is most often high, and low where

the sea is most often low; this is, in fact, the general rule for all parts of the ocean at all seasons. Thus, a high swell is reported locally south of Japan, across the mouth of Bering Sea, and off the Alaskan bight as often as one-fifth of the time in August, much as is true of the sea. Similarly, a heavy swell is encountered somewhat more often in the coastal belt off southern California, and off southern Alaska, than it is in the intervening regions, while the irregular area along the Trades, eastward and westward from the Hawaiian islands, outlined in plates IX and XI by the contours for 10 percent "high," is much more extensive for swells than for the seas of which they are reminiscent; a discrepancy of this sort has already been discussed for the Atlantic (p. 76). The regions in the western side of the Pacific in mid-latitudes, where swells and seas run high more than 10 percent of the time likewise correspond, in general, one with the other, though their precise boundaries differ considerably for any particular frequency that might be selected; this is due partly, no doubt, because the term "high" has a different meaning in the one case (12 feet and over for swells) than in the other (8 feet and over for seas), but chiefly because waves that have lost the characteristics of a sea so commonly continue to advance for long distances as a swell.

The swell, also like the sea, runs high considerably more often in summer in the waters between Japan, the China coast and the Philippines in the one side of the Pacific than it does along the coasts of Central America and of Lower California in the other. The consequence is that vessels crossing in summer from Canadian and Californian ports to Japan and to China may expect to find the swell low during more than half of the time until they cross longitude 180°, beyond which the swell is likely to be low somewhat less often, and high somewhat more so (10 percent or more). But the swells, encountered by ships crossing from San Francisco or Los Angeles to the Hawaiian Islands, are likely to be rather heavy for something like one-tenth of the time during the entire voyage, and low considerably less than one-half of the time.

At the other extreme, the swell is so seldom heavy enough to be of any practical account along the western sector of the equatorial belt of the North Pacific that such of the August reports as mention it at all there class it as "low" more than 80 percent of the time, all along from about the longitude of the Gilbert group westward to the Moluccas and to the southern Philippines; nor do any of the August reports mention a high swell at all within this general region. And since the August sea also is reported "low" there, for 63 to 93 percent of the time, and never "high," the region bounded in plate XII by the contour for 80 percent low, may be named the most pacific part of the ocean of that name of any considerable extent north of the Equator.

Agreement between the two classes of waves is also close in the eastern side of the tropical Pacific, from the Equator northward coastwise to southern California.

Perhaps the difference chiefly deserving of emphasis between the August picture for swells for the North Pacific and that for seas (since it might not appear from a cursory survey of the respective charts) is that a high swell has been reported more than 10 percent (locally as often as 38 percent) of the time, between the Equator and latitude 5° N., westward from the Galapagos Islands, where a high sea has not been reported at all in any of the returns for the month.

The swell is reported as more commonly high in the southern part of the Sea of Okhotsk (20 percent) than the sea is (0 percent high) and less commonly low there. A high swell is also reported somewhat more often (11 to 19 percent) than a high sea (9 to 13 percent) in the eastern and southeastern parts of the South China Sea. But there is no great difference in the frequencies with which high swells and seas are reported near the Asiatic mainland in this region (0 to 10 percent for swells, 1 to 14 percent for seas). Neither is there any greater difference in the relative prevalence of low swells in summer, as compared with low seas, either for the South China Sea or for the Japan Sea, than can be charged to the fact that this category includes a much wider height range for swells than for seas (p. 71).

Winter.—The sea is much more commonly rough in middle and high latitudes of the North Pacific in winter than it is in summer, as might be expected from the stormier weather; in fact, it has been described as "high" in 40 to 60 percent of the late winter reports that have been received, not only across the Alaskan bight, but throughout most of the northwest part of the Pacific down to latitude about 30° N., except along the Japanese island chain, where it is high rather less often even at this time of the year (12 to 36 percent). Ships crossing from Yokohama to Seattle or Vancouver may thus expect a rough sea something like half of the time, except, perhaps, as the American coast is neared, and even higher than 20 feet during winter gales, according to evidence from other sources.[27] And winter crossings from Japan to San Francisco are also likely to be rough, after the first couple of hundred miles and until the longitude of the eastern Aleutians has been left behind, after which it is likely to be smoother, especially nearing the California coast, where a high sea has been reported only about 10 to 14 percent of the time, even in winter.

The most widespread evidence, however, of the increasing roughness of the North Pacific, through the autumn, is that the boundaries

[27] The reported frequency of 10 percent, for seas higher than 20 feet, south of the Alaskan Peninsula in the latitude of Oregon (p. 21), is for the year as a whole; actually, however, so heavy a sea is encountered much more often in high latitudes of the Pacific in winter than in summer, just as it is in the Atlantic.

within which a high sea is reported during more than 20 percent of the time expand, by February, to include the whole vast area southward to the latitude of southern Japan in the west and to that of Lower California in the east (to about latitude 25° N.), excepting only for the smoother tongue that still intervenes between it and the United States coast, in the east, as just noted.

The southern limit of this tumultuous region does not differ much in position anywhere across the Pacific from the corresponding boundary of the area where severe winter gales have been reported on more than 5 days out of 100 during past years. Indeed, it is only where the frequency of gales of force 8 is greater than 10 percent that consistent reports have been received of high seas with frequency greater than 35 percent from any part of the North Pacific at any time of year.

The autumnal roughening of the ocean is also accompanied by a reversal in the relative frequencies with which the sea runs high in the coastal belts of the two sides of the Pacific in mid-latitudes; in summer, this happens more often along the California coast than along the Japanese (pl. IX), whereas in February the reverse is true (12 to 31 percent high along the Japanese islands, 3 to 14 percent high from southern California to Puget Sound).

The greater frequency of high seas in the waters between Japan, Korea, the China coast, and the Philippines in February (0 to 28 percent) than in August (0 to 13 percent) reflects the general increase that takes place there through the autumn in the average strength of the wind, rather than the effects of typhoons, for these seldom develop there in winter. The expansion that takes place from summer to winter of the area within the Northeast Trade Wind Belt, where a 9-foot sea is more than an exceptional event (see the contours for 10 percent "high," pls. IX and XIII), has a similar cause. And gales of moderate strength (force 7 or higher) blowing more commonly in winter (up to 10 percent) off southern Mexico, than in summer, are no doubt responsible for the fact that high seas are reported a little more often off the Central American coast from Costa Rica northward (up to 7 percent) in February than in summer (1 to 3 percent). Well-known examples are the rough seas generated in the Gulf of Tehuantepec by the gales, known locally as "Tehuantepecers," that blow out from the land there in late autumn and winter at times when cold air masses are flowing in sufficient strength southward from the North American continent, and along the western side of the Gulf of Mexico, to be funneled, as it were, across the Isthmus of Tehuantepec.[28] The

[28] See Hurd, 1929, Monthly Weather Review, vol. 57, No. 5, p. 192, for a readable account of these "Tehuantepecers."

swells generated in this way are sometimes reported southward as far as the northern coasts of the Galapagos Islands.

It also seems likely that the 20-foot seas, or higher, that are reported for the equatorial belt southeastward from the Hawaiian Islands, with 4 percent frequency for the year as a whole (p. 21, table 8), actually develop there most often either in September or in February, these being the only months when gales of even moderate intensity (force 7 or stronger) are reported there, other than on the rarest of occasions. The reported frequencies, however, of high seas in low and mid-latitudes in the eastern half of the North Pacific in midocean give no hint of the severe cyclonic storms that occasionally blow there in winter; the Pilot Chart shows the tracks of three such that developed to the north of the Hawaiian Islands in the month of February, during the period from 1922 to 1936.

A corollary of the increasing frequency with which high seas are reported in the northern Pacific, through the autumn, is that the only regions where a low sea is reported as often as 40 percent of the time by February are an isolated pool in the latitude of the northern Philippines, of Formosa, and of southern Japan in the west, and the general offing of the American coast, southward from middle California, in the east. This last is also the only extensive area in the North Pacific where a perfectly smooth sea has been reported in winter during so much as one-twentieth of the time, though the few reports received suggest that this may likewise apply along the equatorial belt in the western side of the Pacific, where calm weather is equally common.

Reports from the Sea of Okhotsk for January or February were not numerous enough to be considered representative. The northern and eastern parts of the Japan Sea are, however, much rougher in winter (high sea 14 to 20 percent) than in summer, as is also the northern part of the South China Sea (high 9 to 15 percent). The sea is, however, as constantly smooth at the entrance to the Gulf of Tonkin in winter as it is in summer, which applies equally along the Bornean coast to the southward, as well as to the waters between the southern Philippines and Celebes.

The question, "How does the North Pacific compare for roughness in winter with the North Atlantic?" is one often asked. During severe winter gales the sea may be expected to rise about as high in the one ocean as in the other; seas, however, more than 20 feet high have been reported considerably more often along the northern routes in the North Atlantic for the year as a whole (13 percent) than for the North Pacific (9 percent), the gales of winter being chiefly responsible in each case. On the other hand, the area where high winter seas have been consistently reported during more than one-fifth of the time extends something like 300 miles further southward in the Pacific in

the late winter (to about latitude 30° N.) than in the Atlantic (only to about latitude 35° N.). High seas are also considerably more frequent in middle and low latitudes in the western side of the Pacific, from southern Japan to the northern Philippines (5 to 28 percent) than they are in the corresponding belt in that side of the open North Atlantic, i. e., from northern Florida to French Guiana (2 to 11 percent). Other than this, however, the winter seas of the Northeast Trades average high about equally often in the one ocean as in the other, except that the east-west gradation is, of course, condensed within a much shorter distance in the North Atlantic than it is in the North Pacific; and the Doldrum Belt is smooth about as constantly in the one ocean, off equatorial West Africa, as it is in the other, of Central America.

The increase that takes place in the frequency of high seas, through the autumn in middle and high northern latitudes is mirrored so closely in the swell that by midwinter the latter runs high during 40 to 60 percent of the time throughout the north central portion of the Pacific as a whole. Indeed, the only extensive regions where the swell has not been definitely reported "high" during at least 10 percent of the time, for the open North Pacific in February, are in its western side from southern Japan southward along the Philippines, and in the general offing of the American coast in the east, from southern California to the equator. It is probable, however, that this also applies to the equatorial belt, westward from about longitude 180°, for a high swell was reported in only 1 out of 62 returns that were received thence for January and February.

Corresponding to this greater frequency of high swells, low swells are encountered considerably less often over the Pacific as a whole, southward to the latitude of middle Japan in the one side and to that of middle California in the other, in February (9 to 44 percent) than in August (34 to 80 percent); this applies also in the Trades, and along the equatorial belt in the west, wherever, a significant number of reports have been received.

On the other hand, the smooth area in the American side of the equatorial Pacific, where the swell is low during more than four-fifths of the time, is much more extensive in winter than in summer (contours for 80 percent low swells, pls. XII and XVI). A swell, larger or smaller, is, however, mentioned in 70 to 90 percent of the winter returns, except along Japan, as well as here and there perhaps in the equatorial belt in the west, and locally in the Panamanian region in the east. Hence it appears that no considerable part of the open Pacific is ever wholly free from a swell at this time of year, a low one being so inconspicuous a phenomenon that it is apt to be ignored,

especially if a sea of any considerable size is running upon it, as so commonly happens.

No reports of swell were received for the Sea of Okhotsk for January or February. In the Japan Sea, a high swell is more common in winter (0 to 10 percent) than at the end of the summer (0 percent). Little change take place, however, in this respect, from summer to winter at the mouth of the Yellow Sea, while the most noticeable alteration, in the swell pattern of the South China Sea, from the one season to the other, is that the belt where a high swell is the most common (upwards of 10 percent) withdraws northward, away from the coasts of Borneo and of Palawan. And the frequency with which the surface has been reported as wholly free from swell, alters but little from summer to winter in any partially enclosed seas of eastern Asia (table 23).

TABLE 23.—*Percentage frequency with which unit areas of the Japan and South China Seas have been reported wholly free from swell in summer and winter*

Area	Percentage frequency of no swell					
	Maximum		Minimum		Average	
	August	February	August	February	August	February
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Japan Sea	58	39	22	32	50	34
South China Sea	50	30	0	0	33	21

SOUTH PACIFIC

The reports from the South Pacific were so few in number that it is doubtful whether such month-to-month differences as they indicate are of much significance, while large areas are necessarily left blank on the charts (pls. IX to XVI). Combination, however, of the reports for July with those for August, yields a pattern consistent enough to be accepted as representative of the late summer state.

Features of the July-August charts (pls. IX and X) of special interest are: (*a*) the demonstration that the west equatorial smooth belt (contour for 60 percent "low" seas) is confined even more closely to the vicinity of the equator in the Southern Hemisphere than in the Northern; (*b*) the delineation of the approximate boundaries of the midequatorial "pool" where high seas are reported during more than 10 percent of the time at that season of the year, with waves even as large as 20 feet occasionally (p. 88); and (*c*) the illustration of the prevailing roughness, in general, of the southern half of the South Pacific during the months in question, when winds averaging up to 16 to 18 miles per hour in velocity, northward as far as about latitude 30° S., generate high waves more than one-fifth of the time, equatorward past

northern New Zealand and as far as about latitude 20° S. in the mid-longitudinal belt of the ocean.

It is much to be regretted that the data are not sufficient to extend the July-August survey farther southward for the mid-Pacific. Conditions, however, along the Chilean coast (table 24) suggest that seas higher than 8 feet are to be expected during at least 40 percent of the time, during these months, to the southward of the latitude of the Straits of Magellan, generally.

TABLE 24.—*Average percentage frequencies of high seas and swells within approximately 300 miles of the west coast of South America*

South latitude	July–August		January–February	
	Sea	Swell	Sea	Swell
	Percent	*Percent*	*Percent*	*Percent*
0°–10°	0	6	0	1
10°–20°	7	15	0	5
20°–30°	5	23	0	12
30°–40°	9	28	9	18
40°–50°	32	53	24	39
50°–55°	43	42	35	49

The seasonal character of the weather also makes it likely that the waves of 20 feet and higher, that have been reported 15 percent of the time for the year as a whole (table 8, p. 21) in mid-Pacific in the latitude of southern Chile, actually develop there rather more often during the northern summer than during the northern winter.

Other aspects of the South Pacific sea pattern of northern summer deserving attention are that high seas running out from the coasts of Peru and of northern Chile are increasingly frequent, as the average strength of the Southeast Trades increases out from the land, and that the sea is high less often between Australia and the North Island of New Zealand than it is eastward from the latter.

The most interesting aspect of the South Pacific swells of northern summer is that these have been reported "high" considerably more often than the sea has throughout the region of the Southeast Trades, as illustrated by the fact that the average frequency for this category between the equator and latitude 20° S., in July and August, is about 13 percent for swells, but only about 5 percent for seas, with the contrast in this respect between the two classes of waves nearly as wide close in to the South American coast as it is out in midocean. "Rolling down the Trades," an old expression from sailing-ship days, is thus much more than a figure of speech when applied to the South Pacific Trades in northern summer.

The fact that the northern summer swell runs high northeastward from New Zealand on the one side (45 to 91 percent), as well as along South America at corresponding latitudes on the other (20 to 42 per-

cent), considerably more often than the sea does, suggests that this would prove equally true right across the ocean in this belt, as well as to the southward. And this is certainly the case between New Zealand and Australia, where an average July-August frequency of about 30 percent for high swells, but of only about 15 percent for high seas, affords still another illustration of the general rule that wherever the sea runs high for any considerable proportion of the time, the swell may be expected to do so even more frequently. In fact the only areas in the South Pacific of any considerable extent, where a high swell has not been reported in frequency as great as 10 percent, for July and August combined, are off the tropical American Coast in the east, along the equatorial belt in the west, and under the close shelter of the more extensive island groups, such as the Fijis and the Ellices.

The Trades, however, raise a sea higher than 8 feet so much less often in the South Pacific during the northern winter than during the northern summer that the average frequency of the category "high" is less than 1 percent (stated as 0 on the chart), for January and February at 71 out of the 104 squares between the equator and latitude 25° S., from which a significant number of returns were received. Indeed, the maximum reported frequency for high seas for this season, along all this belt, is only 11 to 14 percent (off Australia). The prevailing smoothness of the South Pacific is especially striking at this season off South America, when it is necessary to proceed something like 1,000 miles offshore to find high seas in reported frequency as great even as 3 to 11 percent at any individual square, anywhere to the northward of the latitude of northern Chile (lat. 25° S.). Similarly, the swell is heavy enough to be reported as "high" only about one-third as often in January and February, as in July and August, throughout the Trade Wind Belt of the South Pacific in general, all of which is in line with common experience.

And the seasonal contrast is of this same order for seas in the mid-latitudinal belt as well, for even there the January-February chart fails to show a frequency greater than 20 percent for high seas anywhere to the northward of the latitude of northern New Zealand on the one side of the South Pacific, or of central Chile on the other. And while a high swell is reported rather more frequently in northern winter from eastern Australia out past New Zealand (9 to 35 percent) than a high sea—as is indeed the usual rule—the seasonal alteration from summer to winter is of the same order for high swells as for high seas throughout such other parts of the South Pacific as the reports cover, as illustrated by the smaller areas enclosed by the contours for high swells in 10 percent and in 20 percent frequency in January and February (pl. XV) than in July and August (pl. XI).

Corresponding, too, to this decrease from July-August to January-

February in the frequency of high waves of either category, the east-tropical smooth area, as defined on the charts by the contours for "low" in 60 percent frequency, extends tongue-like, something like 1,800 miles farther out along the equator from the American coast in northern winter than in northern summer for seas, and apparently as far as the longitude of the Marquesas and of the Paumotos (about long. 140° W.) for swells, to judge from such scattered information as is at hand. And a corresponding expansion of the equatorial-American region, where swells and seas alike are low for more than 80 percent of the time, takes place from northern summer to winter.

Ships crossing the northwestern part of the South Pacific in northern winter, or in early spring, must however take account of the possibility that they may encounter the dangerous seas that are generated by tropical hurricanes, for these develop most often there from December to March. Such of these storms as originate in the Coral Sea usually move either toward New Caledonia, or past New Guinea, or—more rarely—southward paralleling Australia; others of great severity occur from time to time in the neighborhood of the Fijian and Samoan Island groups.

NORTH INDIAN OCEAN

Summer.—The chief causes for high seas in the Indian Ocean north of the equator are the winds of the Southwest Monsoon, which blow strongest, and with frequent squalls and gales, from June through August. High seas, therefore, are the most frequent there in summer or just when they are least so in the northern parts of the Atlantic and of the Pacific. Regional differences in the frequency with which a high sea is to be expected during the monsoon season (pl. XVII) are also clearly governed by the prevailing strength of the wind. Thus the region in the Bay of Bengal where 8-foot seas, and higher, are reported during more than one-tenth of the time during July and August, corresponds closely with that where the summer monsoon averages stronger than 16 miles per hour. And the limits between India, Arabia, and Africa, within which a high sea has been reported in frequencies greater than 20 percent, and than 40 percent, for July and August combined, coincide almost exactly with those within which the monsoon averages stronger than 16 and 20 miles per hour, respectively, and where gales of force 7, or stronger, are then the most frequent. High seas, indeed, are reported locally in frequencies about as great (maximum 74 percent) within this general region, during the monsoon season, as they are anywhere in the world; and they rise there to heights of 20 feet or more during about 10 percent of the time (table 8, p. 21). Corresponding to this, we read of the western coasts of Hindustan that all small craft near Bombay are laid up from the

end of May until early in August, when the more venturesome put to sea again.[29] The sea is also higher than 2 or 3 feet more constantly (more than 80 percent) in this part of the Arabian Sea, during the height of the Southwest Monsoon, than happens at any season anywhere else in the Indian Ocean, except in the western part of the Southeast Trades Belt, off Madagascar.

The violent winds of the tropical cyclones that develop from time to time in the Arabian Sea, and in the southern or central parts of the Bay of Bengal, are a second potential source of high and dangerous seas in the northern part of the Indian Ocean. In the Arabian Sea these occur most often during the period of transition between the two monsoons, June through July and October through November, but they are infrequent even then. And while they cross the Bay of Bengal most often from June through November, this does not happen frequently enough to have any appreciable effect on the frequency with which high seas have been reported there; the total number of tropical cyclones reported for the Bay of Bengal in July and August was only 92, for a 25-year period, according to a recent tabulation.[30]

Transition is abrupt, in summer, from the stormy waters of the Arabian Sea through the Gulf of Aden, into the Red Sea, to which the monsoon does not extend, and where the winds of summer average so light (8 to 10 miles per hour)—and with gales practically unknown —that the sea rises only occasionally there to 9 feet. A high sea has, however, been reported rather more often in summer in the Persian Gulf (7 to 8 percent in July and August), for what reason is not apparent, since the wind averages no stronger (less than 10 knots) and gales are no more frequent there in summer than in the Red Sea.

A high swell is reported at least as often as a high sea throughout the North Indian Ocean as a whole during the Southwest Monsoon season, excepting only along the Burmese coast of the Bay of Bengal (pl. XIX).

The contrast in frequency between the two classes of waves is particularly instructive in the northern part of the Arabian Sea, where the high seas generated to the southward, where the monsoon average strongest, assume the characteristics of swells so soon, as they spread, that the latter are reported "high" considerably more often along the coasts of northwestern Hindustan, of Beluchistan, and of Arabia in July and August average about 40 percent) than the sea is (average about 20 percent). Similarly, the swells of summer run high about twice as often in the western side of the Bay of Bengal, northward from Ceylon (average about 18 percent) as the sea does (average

[29] British Admiralty, West Coast of Hindustan Pilot, 4th Edit., 1898, p. 38.

[30] Doraiswamy Iyer, V. 1936. Typhoons and Indian weather. Mem. India. Meteorological dept. vol. 26, p. 97.

about 7 percent); so, too, in the equatorial belt (lat. 0° to 5° N.) clear across from the African coast to the offing of Sumatra (average about 17 percent for high swells, about 7 percent for high seas). On the other hand, it is no more common, in summer, for the swell to run high than for the sea in the Red Sea. in the Gulf of Aden, or in the Gulf of Oman. And the boundaries of the areas within which the summer swell is reported "low" in any chosen frequency differ from those for low seas no more widely than can be charged to the nature of the information from which they have been derived (pls. XVIII and XX).

Winter.—The alteration that takes place, from summer to winter, in the state of the sea in the northern Indian Ocean, with the change of the monsoons, can fairly be described as "spectacular." Thus the northeast winds of January and February average so much weaker than the southwest winds of summer—and with gales so unusual—that a high sea was not reported at all, for January or February, for about one-half of the unit areas (pl. XXI) and the maximum frequency was only 4 percent at any of them, except in the general offing of the Gulf of Aden, where an average wind velocity of 12 to 14 knots, December through February, generates 9-foot seas a little more often (5 to 7 percent). It is also perhaps characteristic that a high sea is reported in 4 percent frequency, in winter, between Ceylon and the northern atolls of the Maldive Group, where we ourselves met a sharp gale in January 1902.

It is not astonishing, with high seas so unusual, that the frequency of "low," in late winter, should be more than 40 percent throughout the entire extent of the North Indian Ocean, except for a circumscribed tongue off the East African coast, and more than 60 percent, except in the southwestern part of the Arabian Sea, locally in the offing of the Gulf of Oman, and southwest of Ceylon (pl. XXII).

The following summary (table 25) illustrates how much smoother during the winter than during the summer (both as to seas and as to swells) those parts of the North Indian Ocean are, where the heights of the waves are ruled by the monsoon wind.

TABLE 25.—*Average percentage frequencies of low and high seas and swells in the Arabian Sea and in the Bay of Bengal in winter and summer*

Season	Arabian Sea				Bay of Bengal			
	Seas		Swells		Seas		Swells	
	Low	High	Low	High	Low	High	Low	High
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
January–February (Northeast Monsoon)	60	2	75	3	76	1	89	1
July–August (Southwest Monsoon)	23	24	25	33	37	9	44	16

SOUTH INDIAN OCEAN

The seasonal alternation in the prevailing state of the sea is of the same order in the South Indian Ocean as in the North, i. e., it is high the oftenest in northern summer, when the northern boundaries of the Southeast Trade Wind Belt and of the Westerlies have both reached their most northerly limits for the year; when the average velocities of both these wind systems are at their highest; and when gales of force 7, or stronger, are the most common in high latitudes.

The sea pattern (pl. XVII) exhibits a rather definite north-south alternation in midocean at this time of year. In the equatorial belt of calms, the sea is high for generally less than 5 percent of the time; in the axis of the Southeast Trades Belt, a high sea is reported in frequency greater than 10 percent (greater than 20 percent of the time where the Trades blow the strongest) and 20-foot waves have been reported 3 percent of the time for the year as a whole (table 8, p. 21); in the Variables, the frequency of high seas averages somewhat less, though varying widely as reported from square to square; and finally, along the northern edge of the Westerlies, the sea has been classed as "high" in 20 to 50 percent of the reports for July and August, together. It is also likely that the sea runs higher than 8 feet for more than half the time along the main sweep of the Westerlies, right across the southern Indian Ocean, from the offing of South Africa, past southern Australia and Tasmania; waves of 20 feet, and higher, have been reported from another source (table 8, p. 21) in 17 percent frequency, for the year as a whole on the route between the Cape of Good Hope and southern Australia.

The chief departures from this fundamentally latitudinal pattern are: (*a*) the sea is much less often high (only occasionally so reported) and much more often low (54 to 90 percent, pl. XVIII) in the waters between northwestern Australia and the East Indian island chain to the north than it is farther westward in this same latitudinal belt, where the Trades are better developed; and (*b*) neither of the two relatively smooth belts—the equatorial and that of the Variables—extends westward as far as the African coast, though high seas are hardly more common there than they are in midocean, at corresponding latitudes.

The swell runs high much more often in northern summer than the sea does, throughout the South Indian Ocean as a whole, notably along the Southeast Trades from the approximate longitude of northern Sumatra (95° E.) to Madagascar (overage 37 percent for high swells, and about 18 percent for high seas); this is no doubt due to the same reason that the Trades swells are high more often than the Trades seas in other parts of the oceans (pp. 79 and 85). And a high swell often

spreads (locally up to 73 percent frequency) northward from the stormy Westerlies to the more placid Variables, where high seas, locally generated, are much less frequent.

The slackening of the Southeast Trades that takes place in northern autumn, during their migration southward, is accompanied by a corresponding alteration in the prevailing state of the sea, so general that the regions, within the Trades, where a high sea is reported in frequency as great as 10 percent, are not only much less extensive in January and February than in July and August, but appear to be confined then to discontinuous pools. A high sea has, however, been reported considerably more often in January and February (22 to 33 percent) than in July and August (10 to 24 percent) off the northwestern bulge of West Australia, where the winds of northern winter average somewhat stronger (14 to 16 knots) than those of summer (less than 12 knots).

The period from January to March is also the chief season of tropical cyclones in the South Indian Ocean. Storms of this character then develop most commonly southward and eastward from the Seychelles in about latitude 10° S., and follow a southerly course, most of them passing east of Madagascar, but a few crossing the island, or following the Mozambique Channel. This is illustrated by the storm tracks laid down on the Pilot Charts for January and February. Tropical cyclones may be responsible, at least in part, for the rather large frequencies in which high seas are reported in winter southward and eastward from Madagascar (10 to 16 percent). But the chance of encountering the heavy seas they generate on any given voyage is small, judging from the fact that only 139 of a dangerous character, or about 3 per year, were reported for these months during the period from 1848 to 1891.

Unfortunately, the winter reports from the northern edge of the West Wind Belt have not been numerous enough, nor distributed evenly enough, to be of much significance. But gales are so much less frequent there in northern winter than in summer as to suggest that 20-foot seas are not to be expected more than half as often from December through February, as in June, July, or August, along the steamer route between South Africa and South Australia, where their reported frequency is 17 percent for the year as a whole (table 8, p. 21).

It seems further that a heavy swell is not as common along the northern edge of the Westerlies in northern winter as it is in summer for the available percentages, derived from scattered data along the route between South Africa and southern Australia, locate the northern boundary of the area where a high swell is to be expected as often as 40 percent or more of the time, in January and February, as lying to the southward of latitude 40° S., except off South Africa and

off South Australia, or something like 300 miles farther south there than in July and August.

The alteration that takes place in northern autumn in the prevailing state of the swell is, however, so much smaller in the southern Indian Ocean than it is in the northern, that the winter gradation, along any longitudinal belt that might be chosen, is regularly from a smaller frequency of high swells and larger frequency of low, in the north, to a greater frequency of high, and a smaller frequency of low in the south. In northern summer, by contrast, a high swell is most common in the extreme northern part of the Indian Ocean, on the one hand, and in high southern latitudes on the other, and least common (and with the swell most often low) along the equatorial belt in general and, locally, in the Mozambique Channel.

The seasonal alteration, from northern summer to winter, in the state of the swell relative to that of the sea, is summarized in table 26 for the relatively calm belt between the equator and latitude about 5° S., as well as for the axis of the Southeast Trades which, roughly speaking, are the best developed between about latitudes 10° S. and about 20° S. in northern summer, but between about 15° S. and about 25° S. in winter.

TABLE 26.—*Average percentage frequencies of low and high seas and swells in the South Indian Ocean, along the equatorial belt and along the axis of the Southeast Trades, in northern winter and summer*

Season	Equatorial Belt				Southeast Trades			
	Seas		Swells		Seas		Swells	
	Low	High	Low	High	Low	High	Low	High
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
January–February	73	1	78	4	42	8	47	18
July–August	57	1	55	14	29	16	32	31

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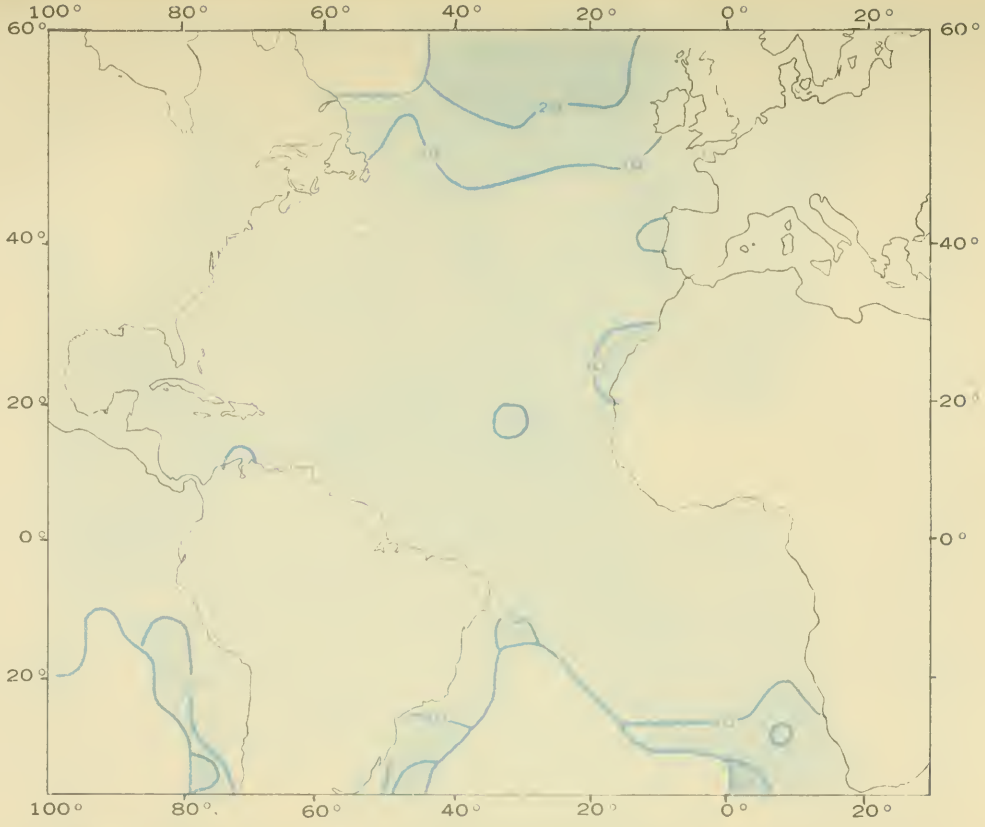

Plate I.—Distribution of high seas in the North Atlantic in August and in the South Atlantic in July and August. Untinted areas are those with insufficient data.

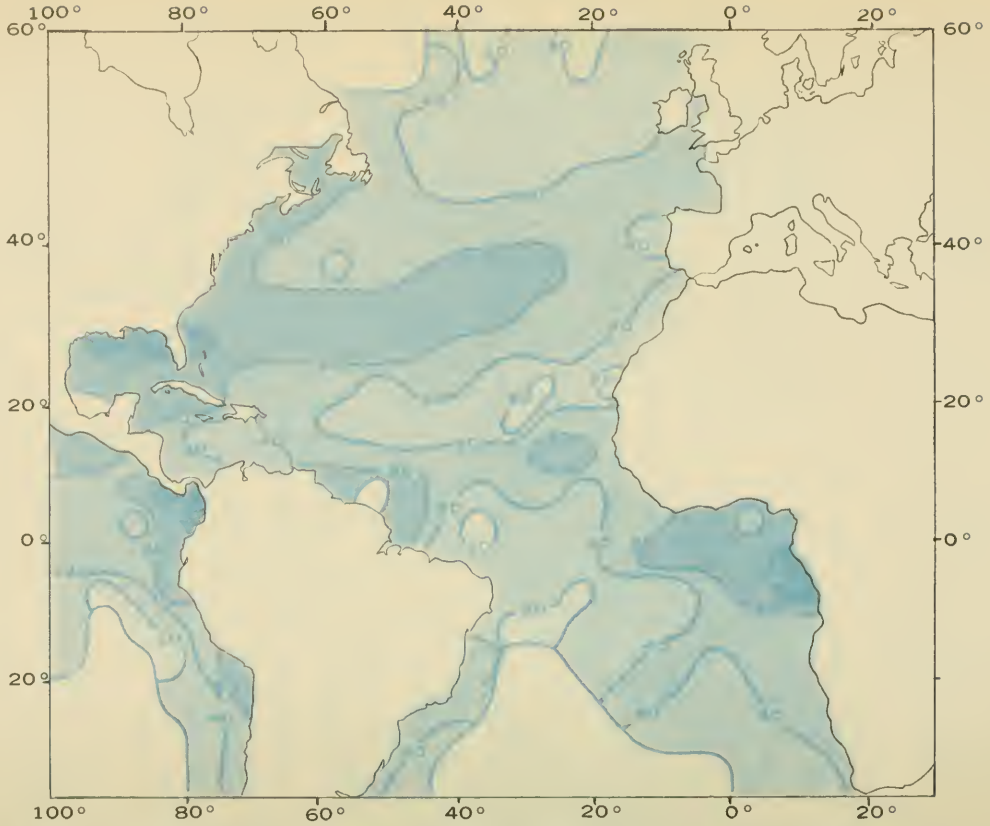

Plate II.—Distribution of low seas in the North Atlantic in August and in the South Atlantic in July and August. Untinted areas are those with insufficient data.

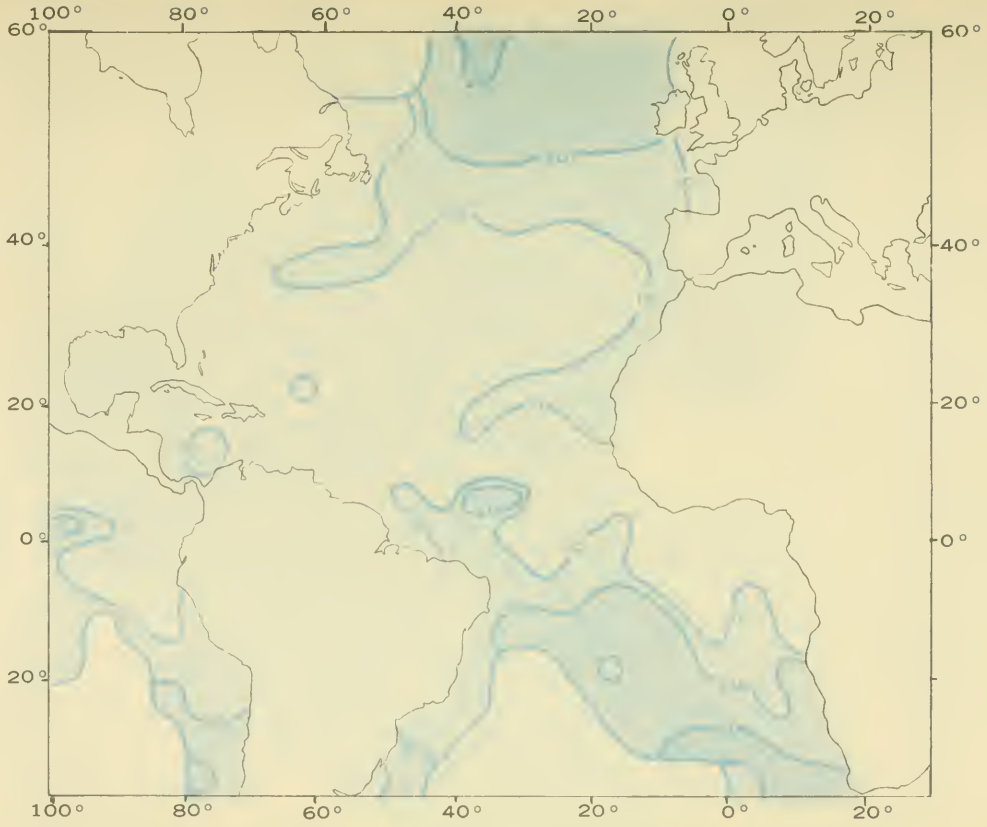

Plate III.—Distribution of high swells in the North Atlantic in August and in the South Atlantic in July and August. Untinted areas are those with insufficient data.

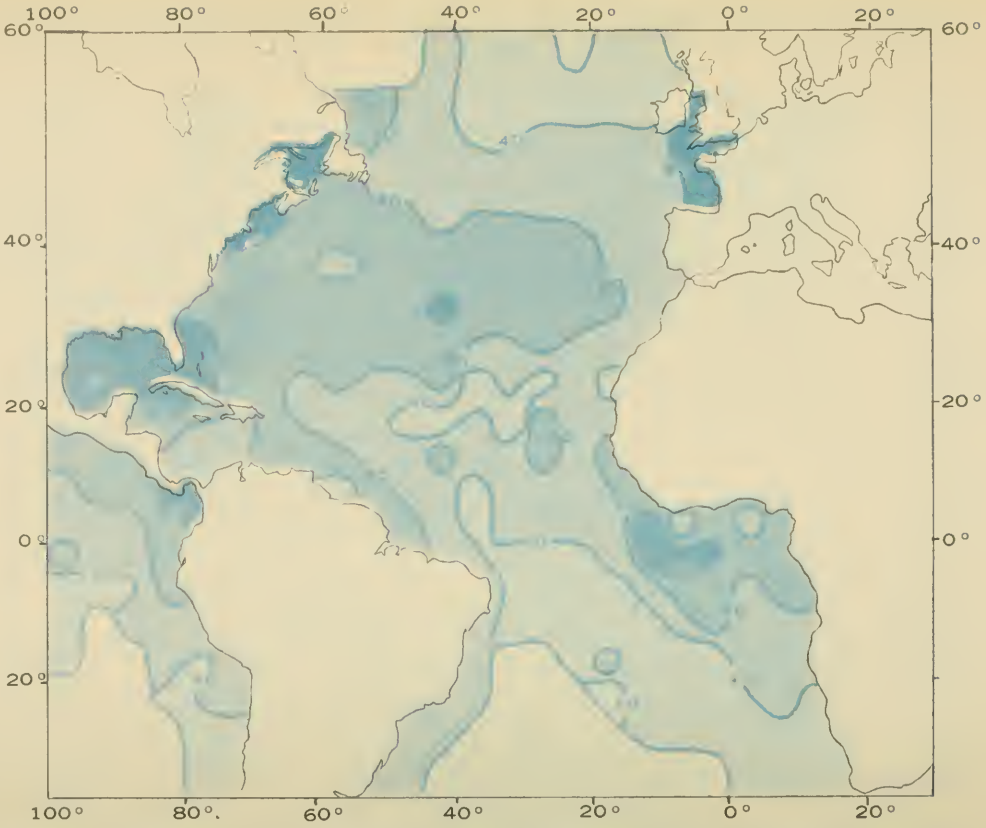

Plate IV.—Distribution of low swells in the North Atlantic in August and in the South Atlantic in July and August. Untinted areas are those with insufficient data.

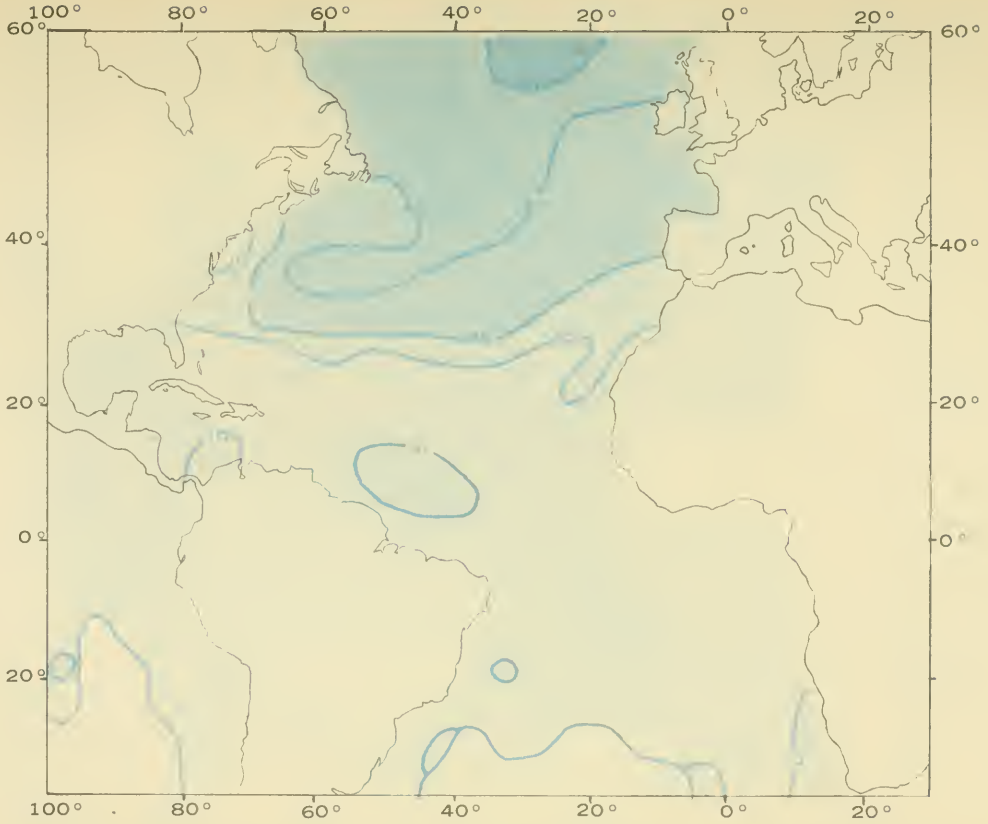

Plate V.—Distribution of high seas in the North and South Atlantic in January and February. Untinted areas are those with insufficient data.

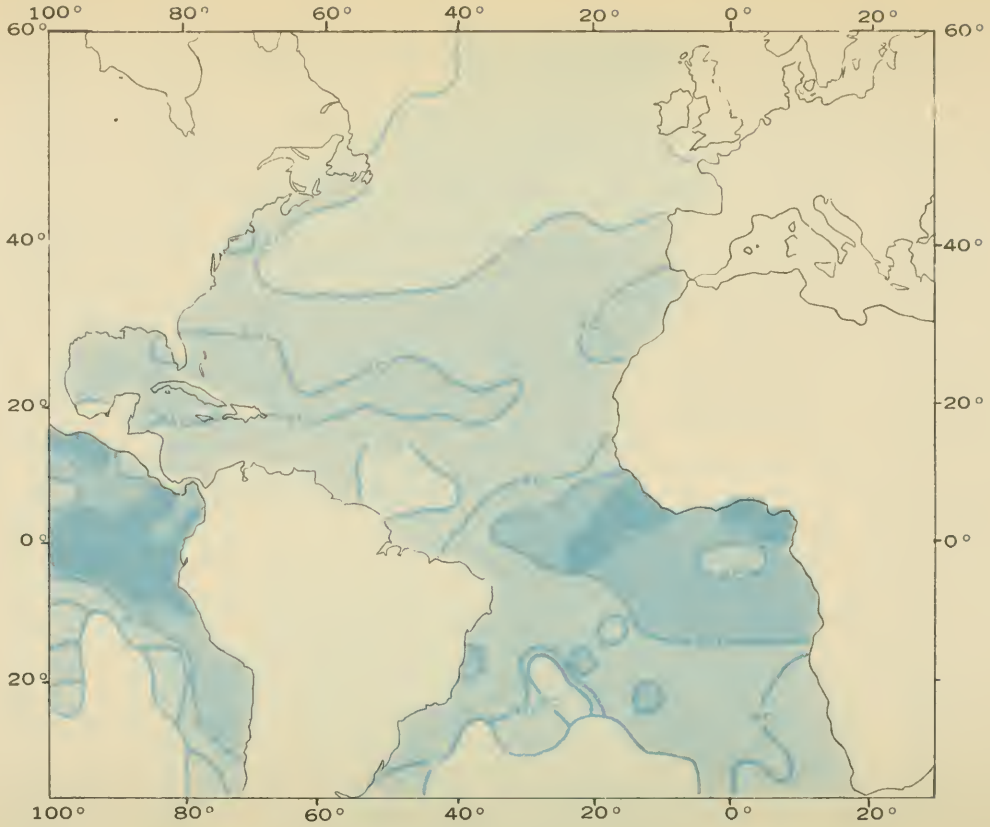

Plate VI.—Distribution of low seas in the North and South Atlantic in January and February. Untinted areas are those with insufficient data.

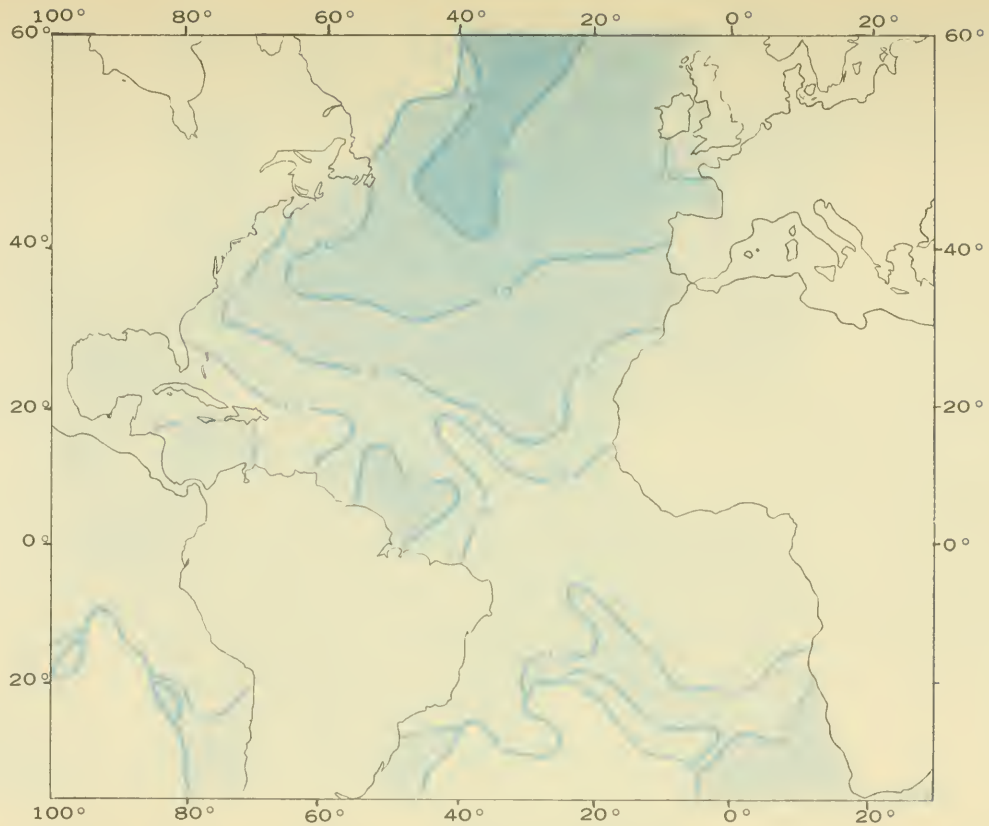

Plate VII.—Distribution of high swells in the North and South Atlantic in January and February. Untinted areas are those with insufficient data.

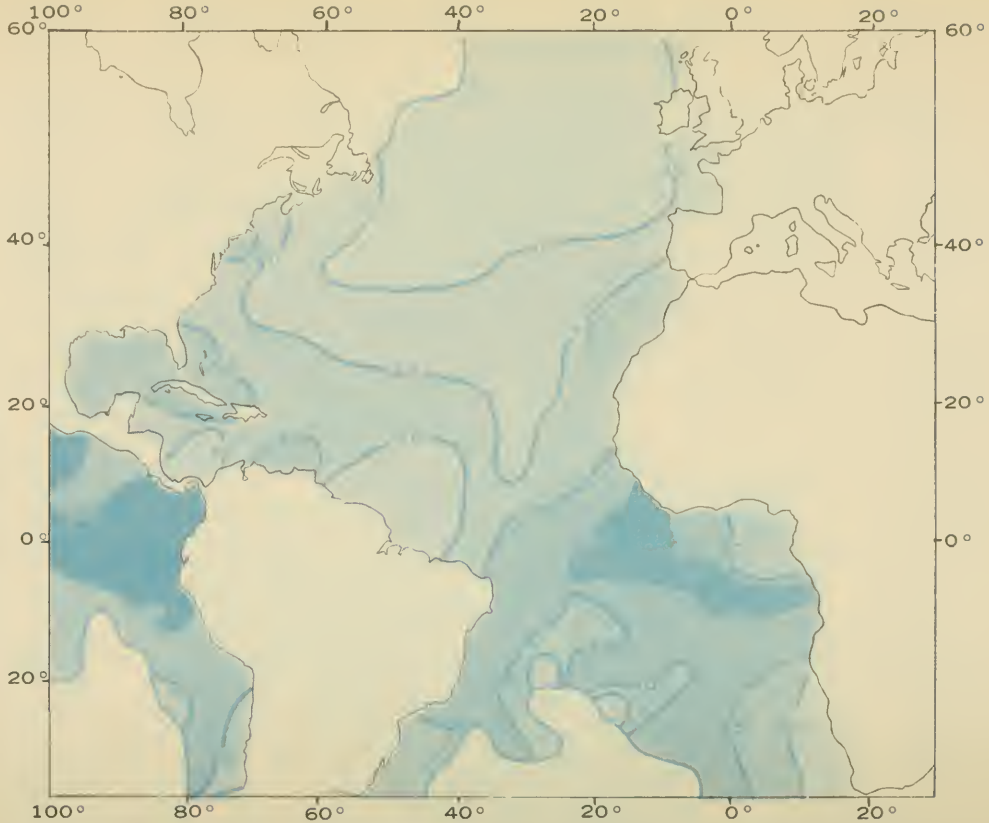

Plate VIII.—Distribution of low swells in the North and South Atlantic in January and February. Untinted areas are those with insufficient data.

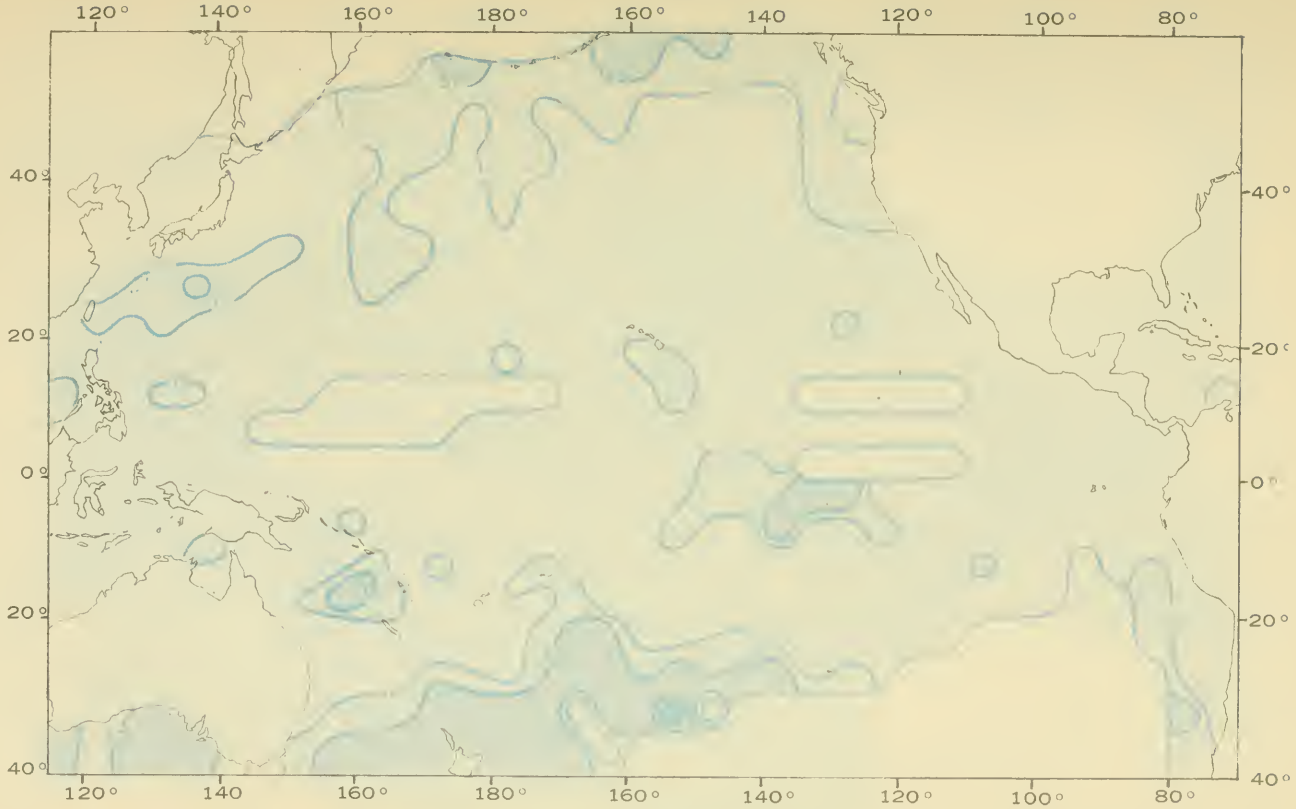

Plate IX.—Distribution of high seas in the North Pacific in August and in the South Pacific in July and August. Untinted areas are those with insufficient data.

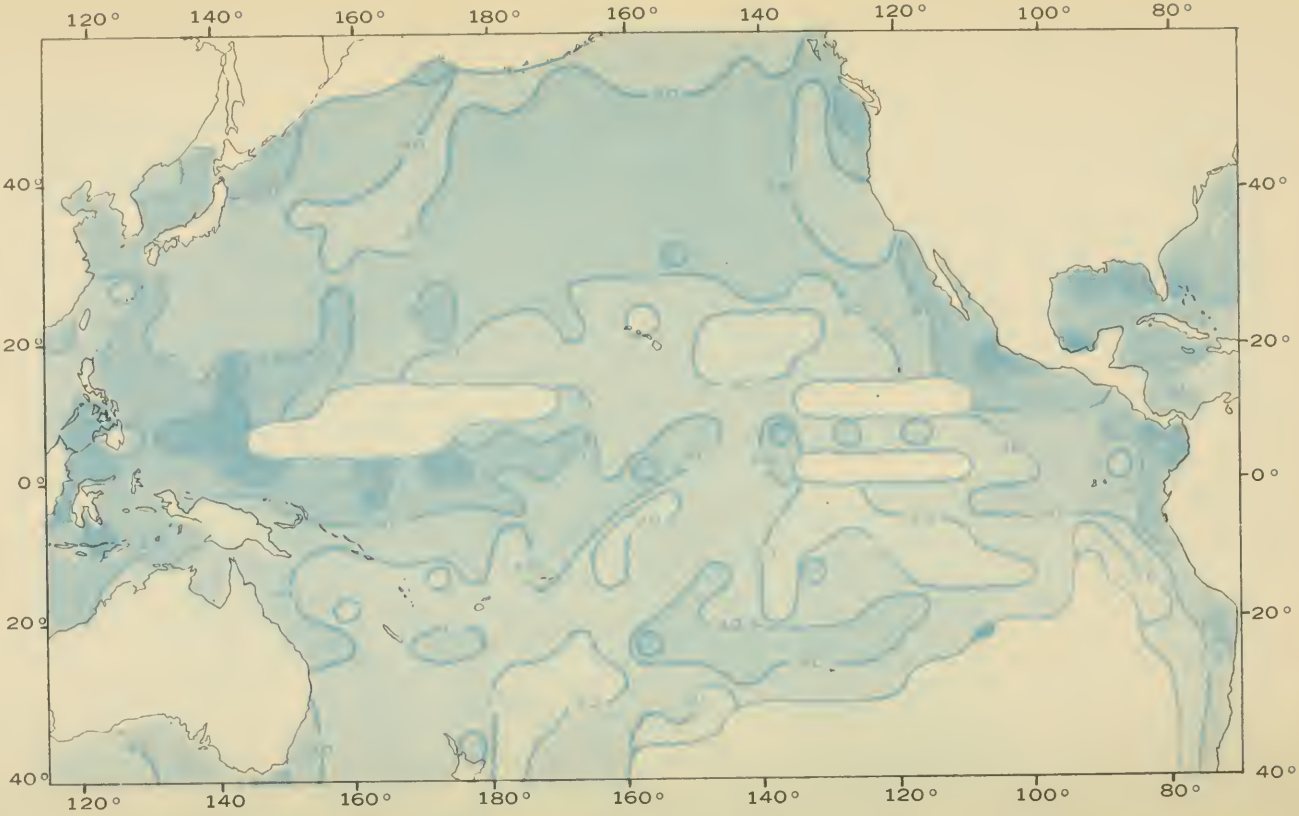

Plate X.—Distribution of low seas in the North Pacific in August and in the South Pacific in July and August. Untinted areas are those with insufficient data.

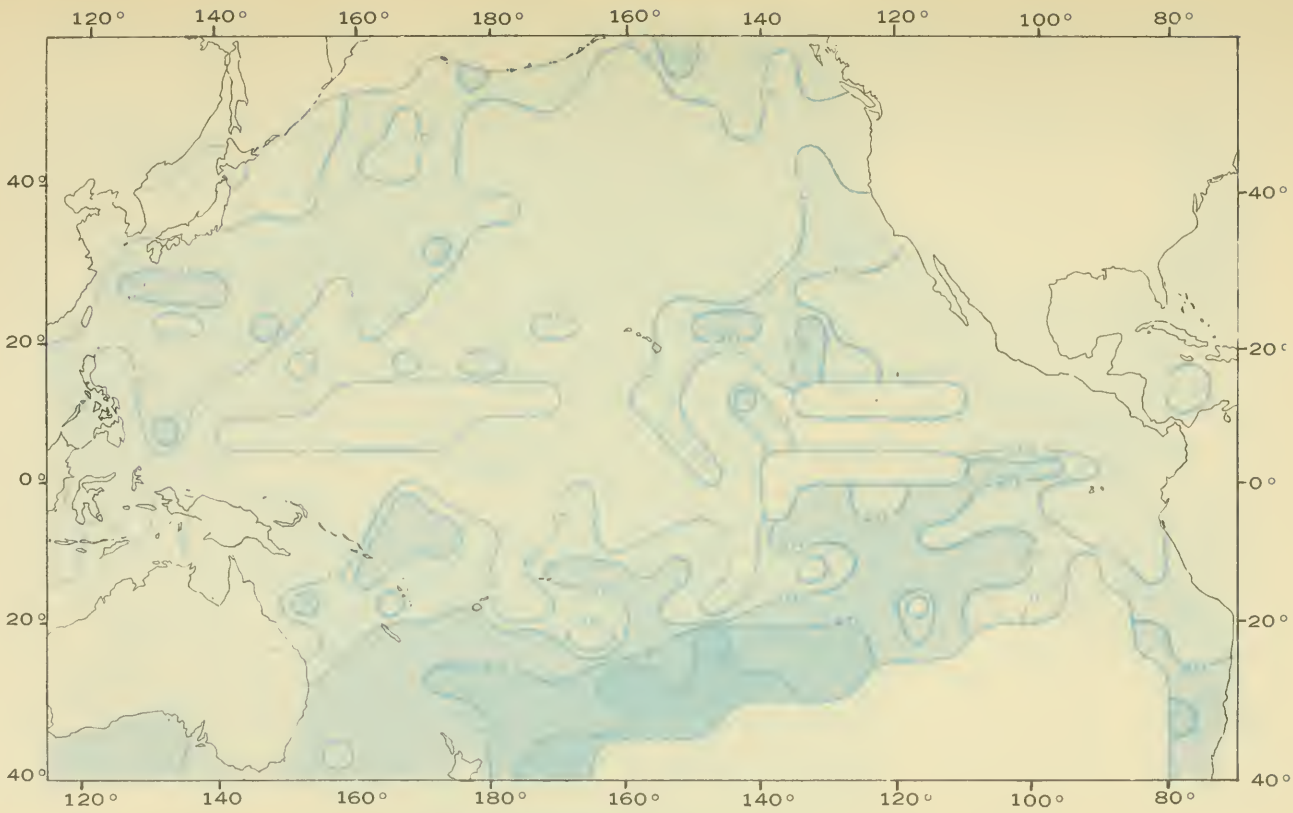

Plate XI.—Distribution of high swells in the North Pacific in August and in the South Pacific in July and August. Untinted areas are those with insufficient data.

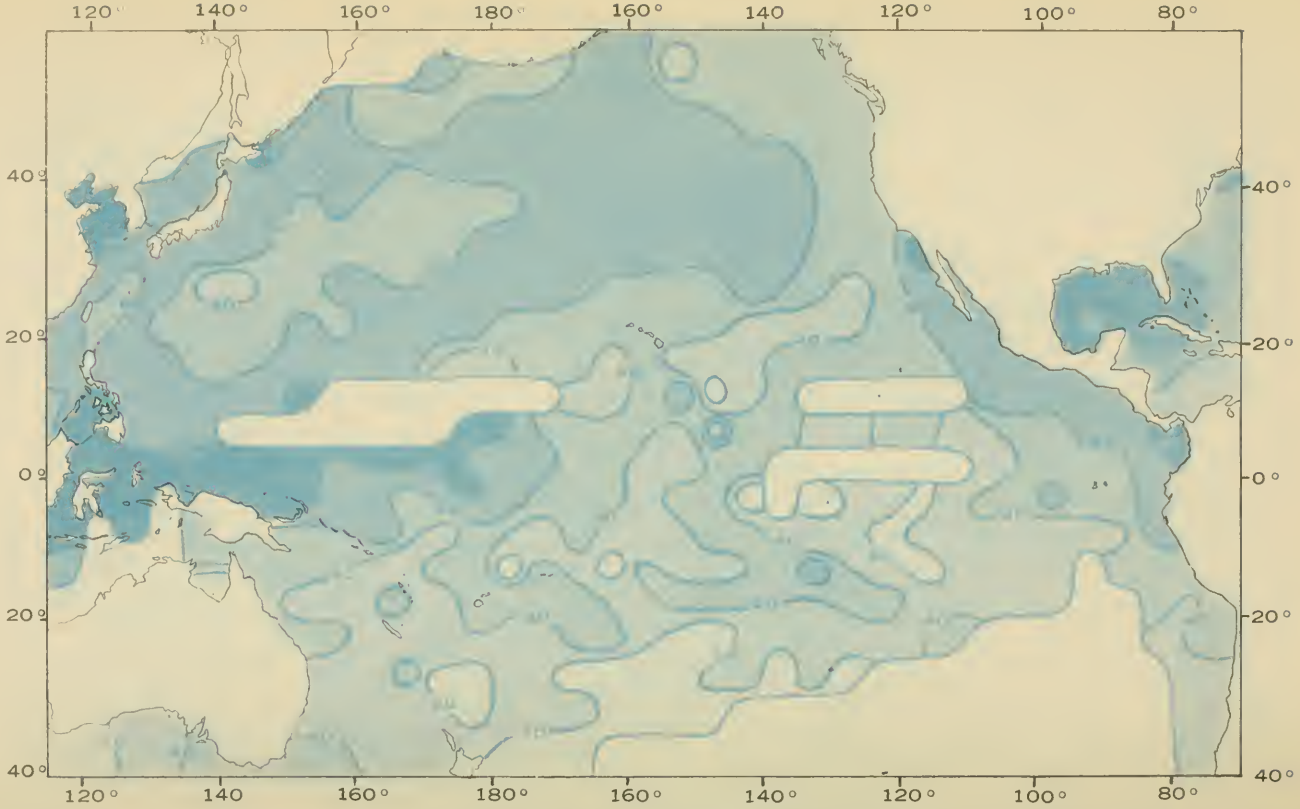

Plate XII.—Distribution of low swells in the North Pacific in August and in the South Pacific in July and August. Untinted areas are those with insufficient data.

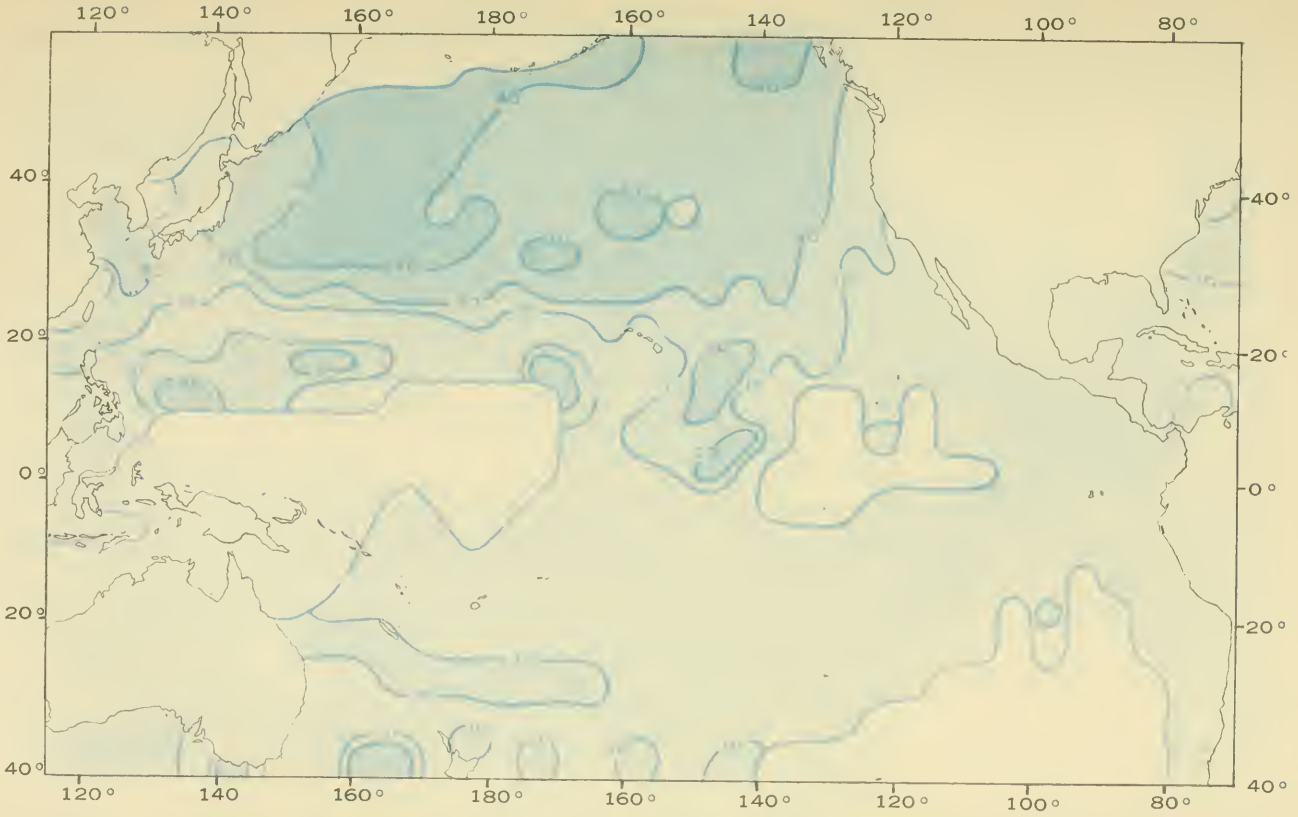

Plate XIII.—Distribution of high seas in the North Pacific in February and in the South Pacific in January and February.
Untinted areas are those with insufficient data.

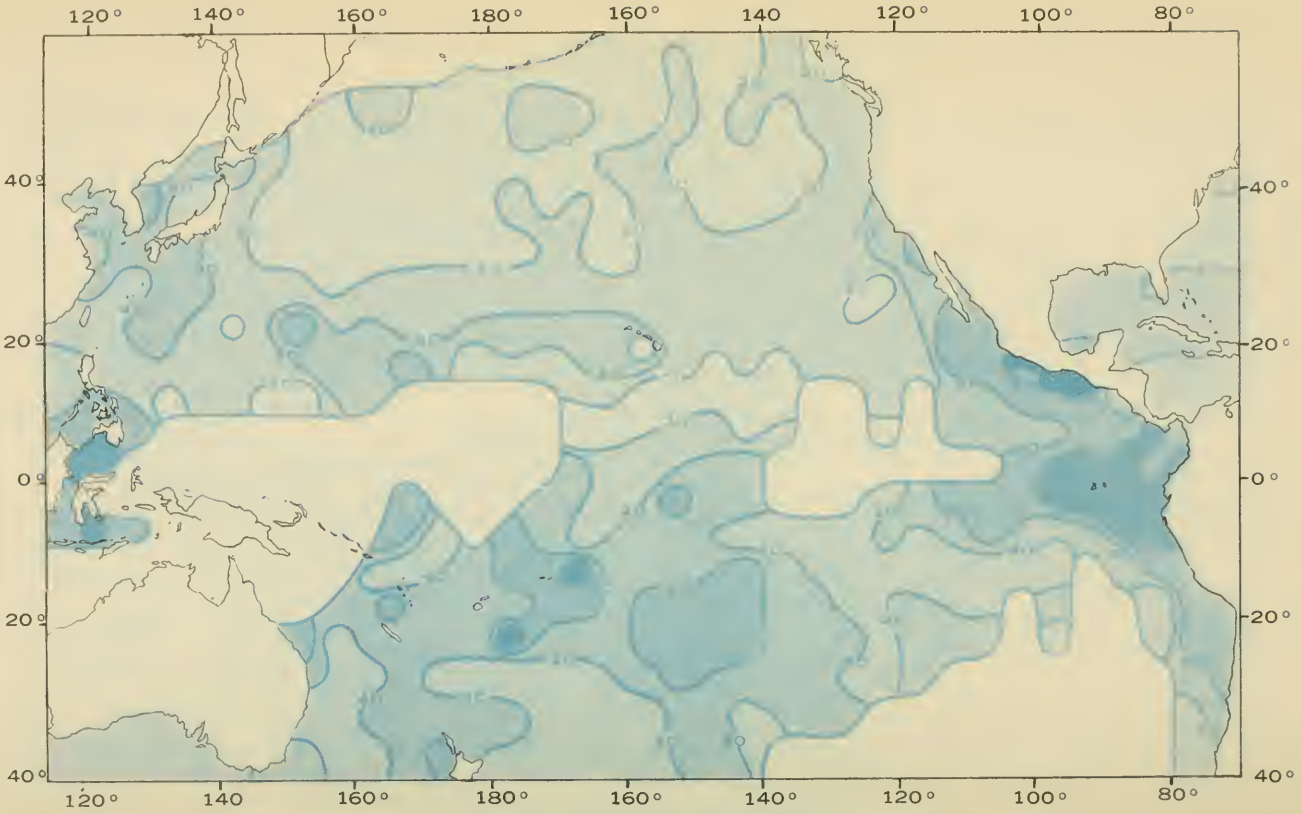

Plate XIV.—Distribution of low seas in the North Pacific in February and in the South Pacific in January and February. Untinted areas are those with insufficient data.

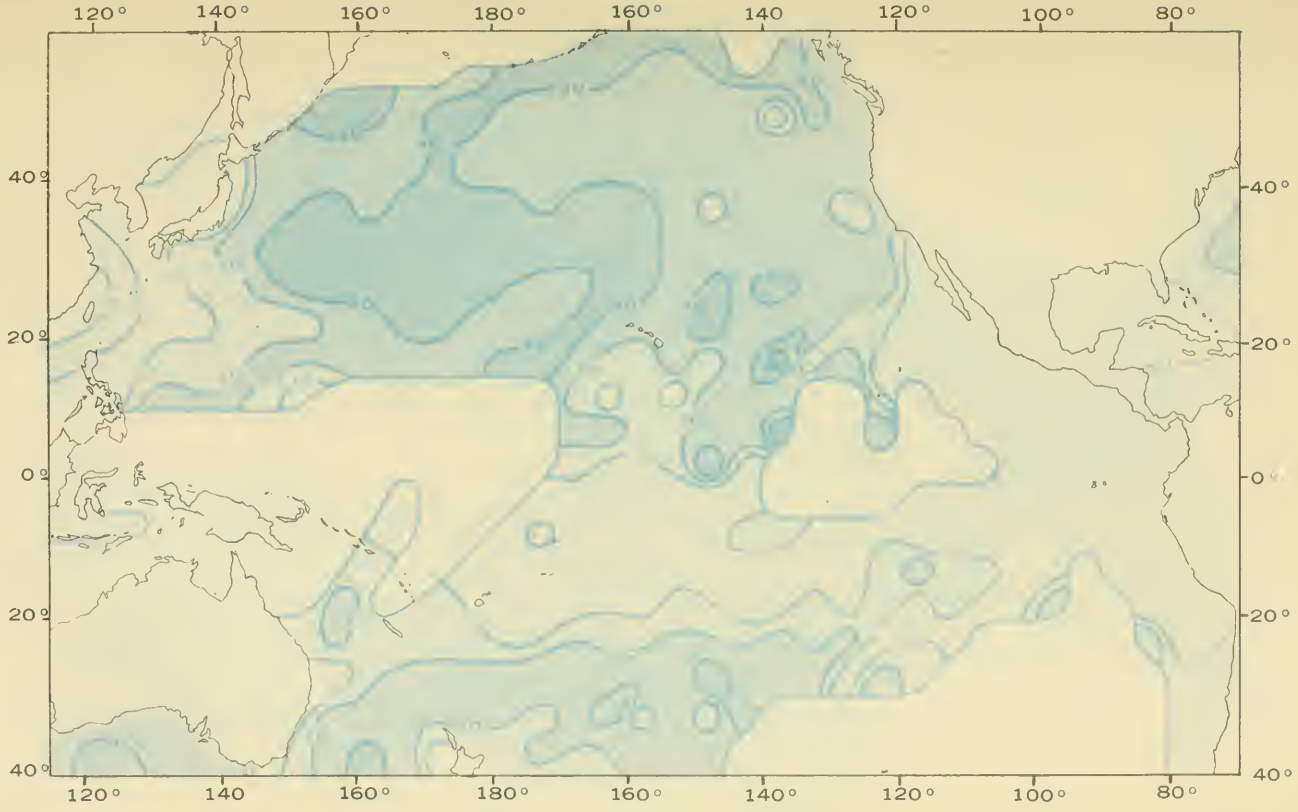

Plate XV.—Distribution of high swells in the North Pacific in February and in the South Pacific in January and February. Untinted areas are those with insufficient data.

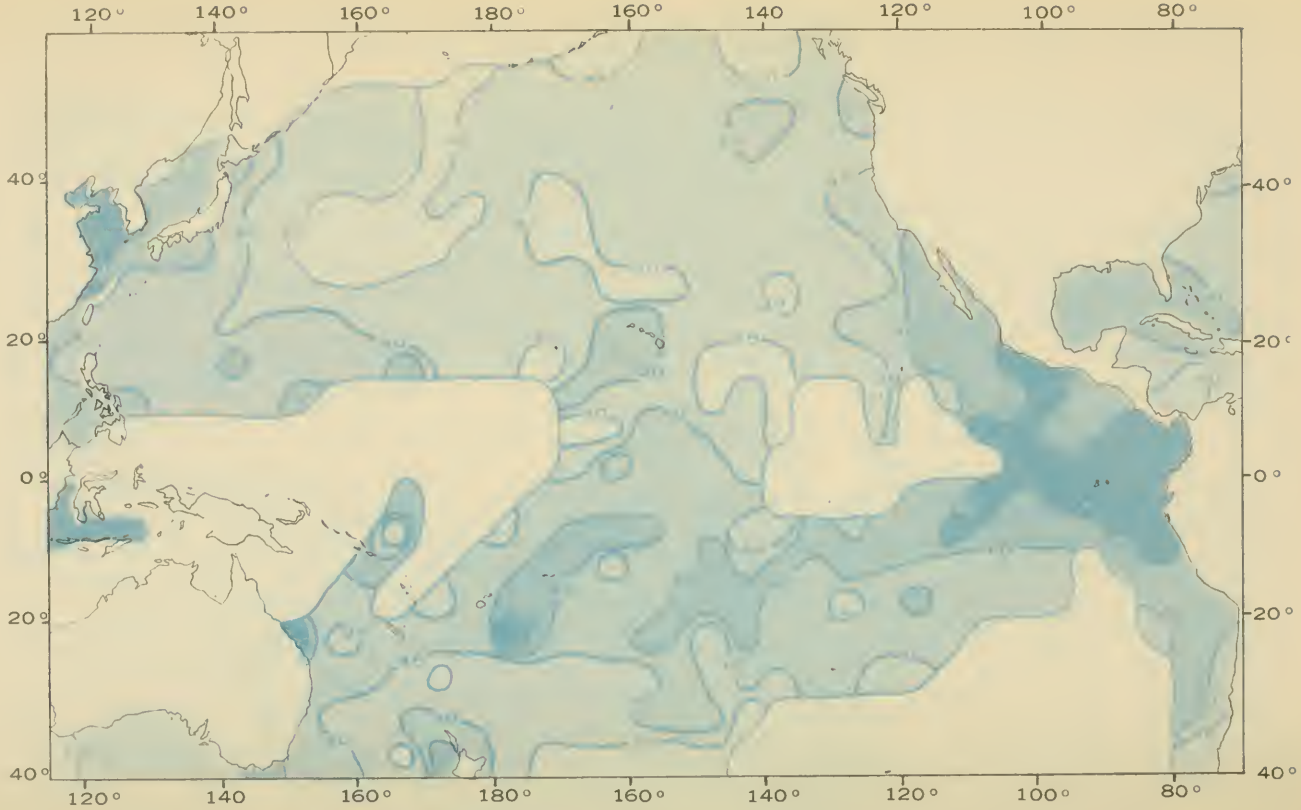

Plate XVI.—Distribution of low swells in the North Pacific in February and in the South Pacific in January and February. Untinted areas are those with insufficient data.

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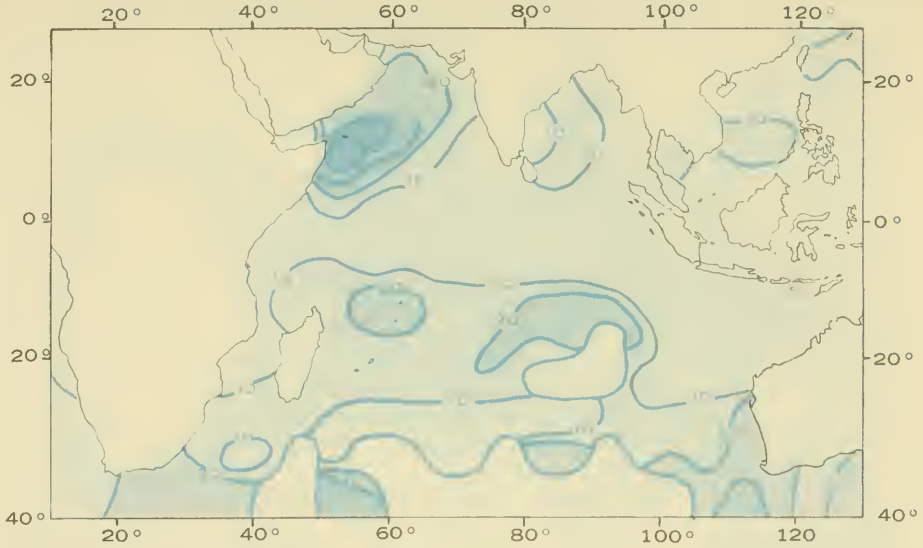

Plate XVII.—Distribution of high seas in the Indian Ocean in July and August. Untinted areas are those with insufficient data.

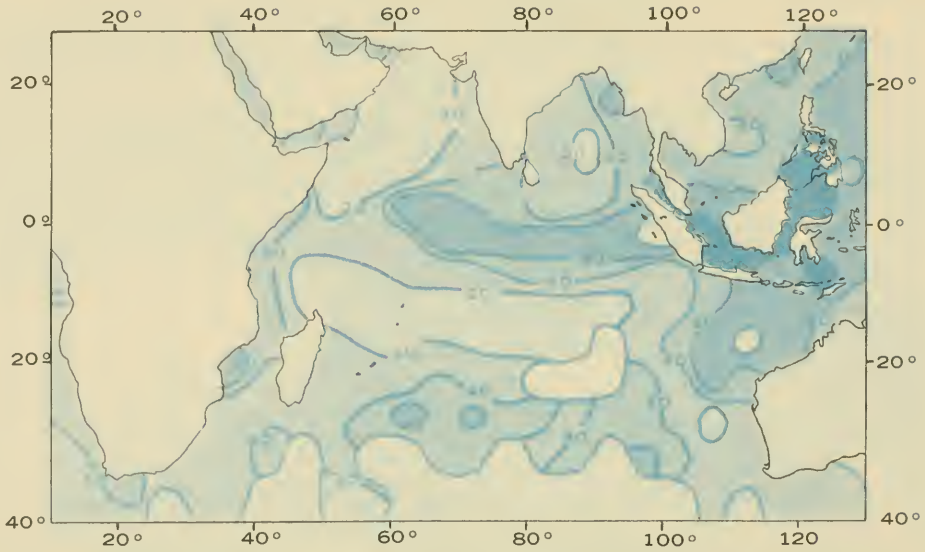

Plate XVIII.—Distribution of low seas in the Indian Ocean in July and August. Untinted areas are those with insufficient data.

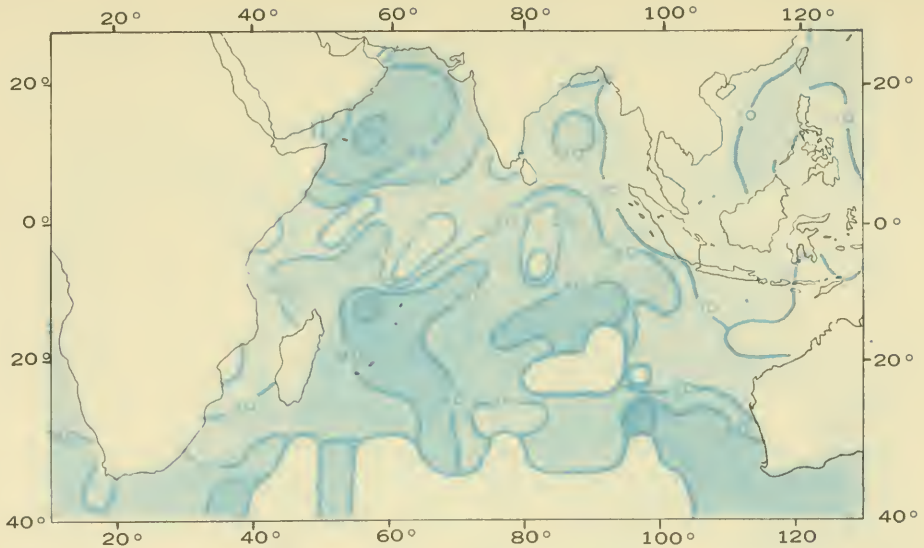

Plate XIX.—Distribution of high swells in the Indian Ocean in July and August. Untinted areas are those with insufficient data.

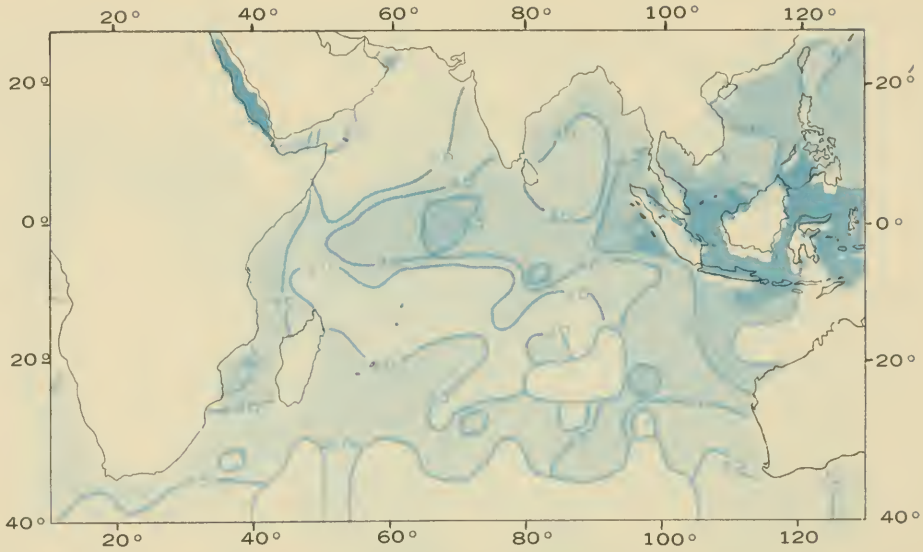

Plate XX.—Distribution of low swells in the Indian Ocean in July and August. Untinted areas are those with insufficient data.

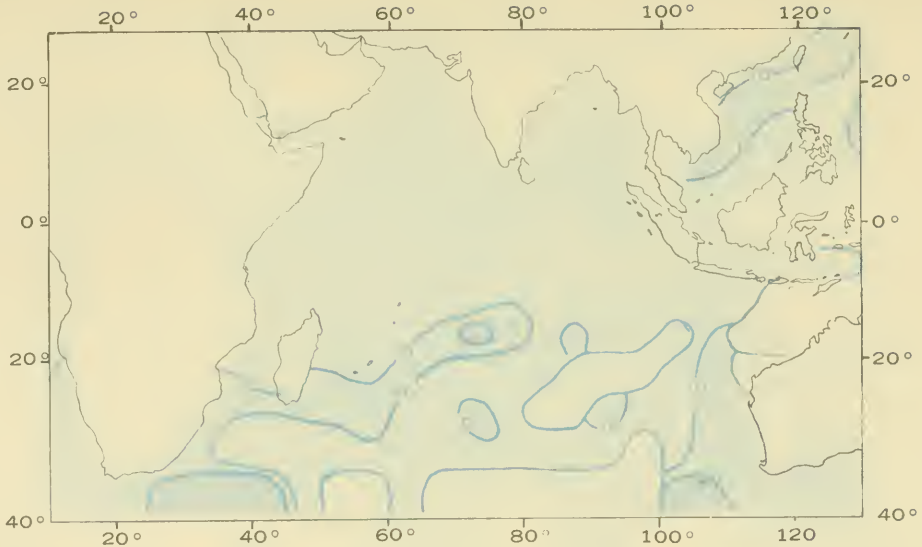

Plate XXI.—Distribution of high seas in the Indian Ocean in January and February. Untinted areas are those with insufficient data.

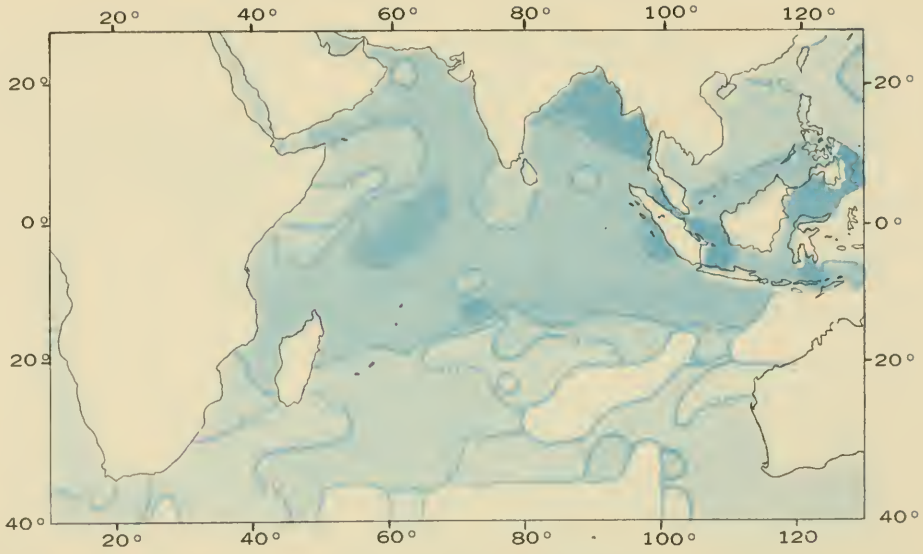

Plate XXII.—Distribution of low seas in the Indian Ocean in January and February. Untinted areas are those with insufficient data.

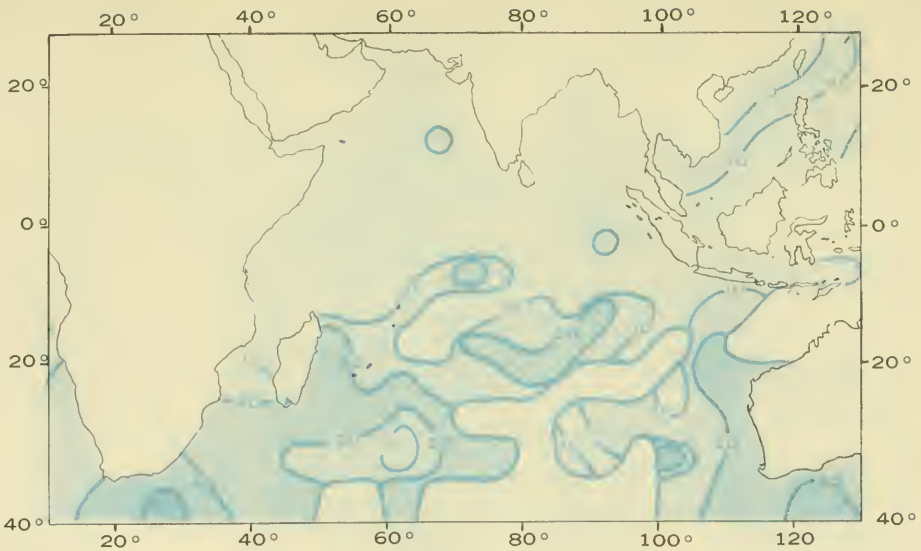

Plate XXIII.—Distribution of high swells in the Indian Ocean in January and February. Untinted areas are those with insufficient data.

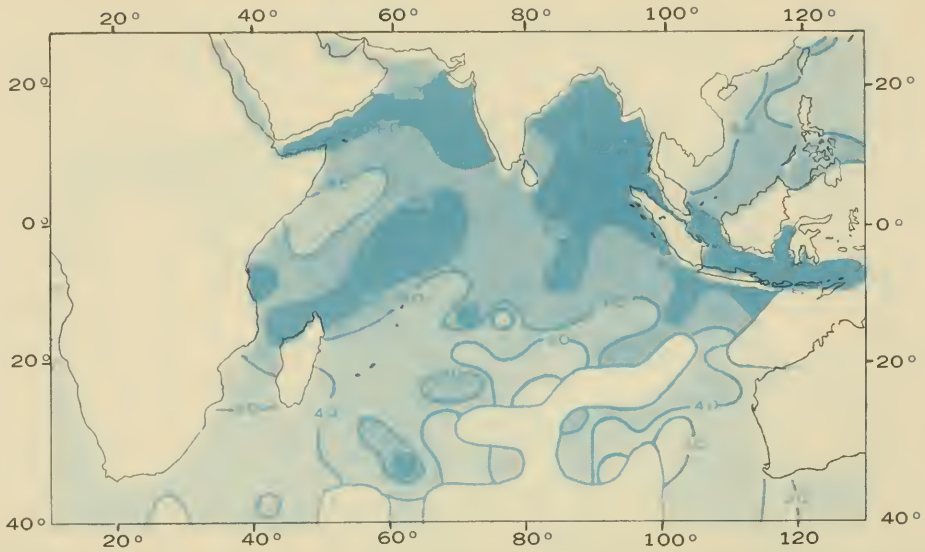

Plate XXIV.—Distribution of low swells in the Indian Ocean in January and February. Untinted areas are those with insufficient data..

Chapter 6

BREAKERS AND SURF; THEIR IMPORTANCE AND ORIGIN

When waves break, whether as a result of advancing into shoaling water or of dashing against ledges or breakwaters, they are known as "breakers," to distinguish them from the storm waves that break out at sea. "Surf" is the name commonly applied to the composite phenomenon when breakers develop in a more or less continuous belt along the shore, or over some submerged bank or reef.

Any type of wave that moves shoreward, or even parallel with the shore line, may produce a surf; whether it will actually do so, in any given case, depends on various factors to be discussed below. In considering surf, it is therefore necessary to include storm waves that may be generated by high winds blowing at the time and place, and also swells that may have come from a long distance, for it is not unusual to encounter a heavy surf in calm weather as well as in stormy.

An observer standing on the shore is in an excellent position to judge the state of the breakers, and most of the published discussions of surf have been from the standpoint of the landsman in relation to engineering problems, such as the construction of breakwaters and sea walls, for example, or in relation to the erosion of coast lines. In the following account we attempt to present the matter from the standpoint of the man at sea, who may have occasion to bring landing craft in to the beach through the surf, or out again through it.

THE IMPORTANCE OF SURF

Breakers, when seen from the seaward, never seem as dangerous as they really are, because a view of their backs gives a very inadequate idea of their heights or steepness; what appears to be a mere swash on the beach, when seen from offshore, may actually be a very dangerous surf indeed. (This point is emphasized in Knight's Modern Seamanship,[31] a book with which every ship's officer ought to be familiar.) A heavy surf also carries an enormous power of destruction; any seaman knows that no one can hold his footing on the deck if it be swept by heavy breakers.

A general knowledge of the characteristics of surf, and especially an ability to forecast its height, is therefore of great importance in

[31] Knight, A. M. 1945. Modern Seamanship. 11*th ed.* New York. p. 388.

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landing operations, for to attempt to bring a boat in through heavy breakers may well be fatal. Surf is also one of the chief factors that must always be taken into account in the construction of breakwaters, of sea walls, of piers, or of other installations on shore lines that are exposed to it. The planning of these structures to withstand the force of the breakers taxes the resources of engineering to the utmost; and even so, severe damage may occur.

The energy of a wave is of a twofold nature: (*a*) "dynamic," or "kinetic," whichever term may be preferred, resulting from the combined momentum of the innumerable water particles of which it is composed, and (*b*) "static," or "potential," due to the elevation of the center of gravity of the wave crest above sea level—to its "head," in other words. Half its energy is dynamic, the other half static, with its total energy proportional to its length and to the square of its height.[32] The total energy, for example, of a wave 500 feet long and 10 feet high is 400,000 foot-pounds per linear foot of its crest; and a wave 200 feet long and 6 feet high would carry an energy of 57,600 foot-pounds per foot at its crest.

The total energy of a wave is slightly lessened when it comes into water shoal enough to alter its form. On the other hand, a considerably greater proportion of its total energy then lies above still water level and moves forward with the wave form; it is largely for this reason that the destructive power of breakers is so great. (For further discussion, see Gaillard, 1904, pp. 45 and 135–136, pl. 5.)

Many measurements have been made with dynamometers, of one sort or another, in the breaker zone along different coasts; these may be typified by the following readings, taken at Skerryvore Rocks, and at Tyree Island, off the west coast of Scotland, in 1845 (table 27). (For a general discussion of the pressures exerted by breakers, see Gaillard, 1904, pp. 124–134 and 145–211.) During the two previous years, the readings averaged 2,086 pounds per square foot in winter, 611 pounds per square foot in summer, a difference that obviously reflects the seasonal difference in the sizes of waves there. The observed values summarized in table 28, for Florida and for Lake Superior, are a further example of the relationship between the dimensions of breakers and the pressures they have been found to exert. Furthermore, dynamometers of the types used in the foregoing experiments measure only the dynamic pressures of the breakers, not the static, i. e., they record only a part of their energy.

[32] According to the equation $E = \frac{1}{4} WLh^2$, where E is the total energy in foot-pounds per unit width of the crest in one wave length, W is the weight of 1 cubic foot of sea water, L is the wave length in deep water, and h is the wave height. For an extensive table, giving the force exerted by deepwater waves of different sizes and shapes, see Gaillard, 1904, p. 41 and O'Brien 1942, p. 14.

TABLE 27.—*Pressures of breakers on west coast of Scotland, in 1845, as recorded by spring dynamometers*

[From Gaillard, after Stevenson]

Supposed height of waves (feet)	Conditions of sea	Dynamometer readings (pounds/square feet)
6	Swell	3,041
10	Ground swell	3,041
20	Heavy sea	4,562
20	Strong gale, heavy sea	6,083

TABLE 28.—*Pressures recorded on spring dynamometers by waves of different dimensions. The first three wave heights (2 to 6 feet) were for the breaker zone at St. Augustine, Fla.; the last three (12 to 18 feet) were for Duluth Canal, Lake Superior, where readings were taken at two different levels relative to the mean level of the lake at the time*

[Adapted from Gaillard]

Height of wave (feet)	Length of wave (feet)	Maximum pressure (pounds/square feet)
2	46	148
4	82	406
6	150	667
12	130–150	250–1,150
16	200–210	1,335–1,755
18	250	2,195–2,370

The force with which a breaker will strike any given object does not necessarily correspond to its total energy; it may, in fact, be very much less, for while the energy of a wave depends solely on its shape and size, the force that it may exert on any obstacle depends on the shape of the object struck, i. e., on how nearly streamline the latter may be, as well as on its size. Thus, a breaker 12 feet high and 200 feet long, which would exert a pressure of 1,600 pounds per square foot on a vertical object lying squarely transverse to its path, such as a barge lying stranded, side on, in the surf zone, would affect the same barge much less, proprtionately, if she were lying bow on.

The obstacles on which waves may beat vary so infinitely in their contours that it is not practical to make exact mathematical calculations of wave force for given cases unless their shapes are very simple. But pressures, such as those tabulated above for St. Augustine, are ample to account for the displacement of concrete blocks weighing 3,600 to 21,600 pounds that actually occurred there during the period of observation, even after due allowance has been made for the shapes of the blocks. And in view of the much higher pressures that have been recorded elsewhere, it is not astonishing that many cases are on record where blocks of stone or cement, or masses of concrete used in breakwaters, have been shifted from their beds for longer or shorter dis-

tances, even up to the almost incredible weight of 2,600 tons, though anchored or fastened in various ways with iron rods. Striking examples, often quoted, are: a concrete block of 20 tons lifted vertically to a height of 12 feet and landed on top of a pier 4 feet, 10 inches above high water mark at the entrance to the canal to Amsterdam Harbor; stones weighing up to nearly 7,000 pounds thrown over a wall 20 feet high at Cherbourg on the southern shore of the English Channel; and —most famous case of all—an enormous mass of large stones set in cement, and bound together with iron rods, the whole weighing 1,350 tons, broken loose and moved bodily at Wick Breakwater, Scotland. (For more extensive discussions of the subject, see Gaillard, 1904, pp. 125–134 and 137–144, and Johnson, 1919.)

Engineers concerned with the design of breakwaters, and so forth, find it necessary to reckon with presures up to 2,280 pounds per square foot in the Baltic; 3,450 pounds per square foot in the North Sea; and 4,120 pounds per square foot in the Bay of Biscay (Krümmel, 1911, p. 118).

THE CAUSES OF SURF

The underlying cause for the development of breakers and surf is the alteration that takes place in the shapes of waves as these move in shoreward over a shoaling bottom, after they have reached the point where the depth is less than one-half their own initial lengths.

This alteration, as summarized on p. 56, consists in a decrease in their lengths, often combined with an increase in their heights, by which their crests are progressively steepened until they break. And waves running toward the shore so commonly advance into water shallow enough to transform them into breakers, that one is apt to forget that the water may continue so deep, right up to the strand, that the drag, so to say, of the waves on the bottom may not be sufficient to steepen them to the breaking point before they actually arrive at the barrier of the shore line. Thus, waves advancing against a steep promontory, or cliff, that rises from water, say, twice as deep as the wave heights, may simply surge up and down against the barrier, breaking not at all or only in a confused manner, unless they strike a part of the barrier where irregularities in its face cause them to do so. It is often easy to observe this phenomenon when small waves are running against a stone or steel pier with sheer walls, and we read that it is sometimes taken advantage of in the construction of breakwaters. Surf breaks heavily, however, against sea walls, etc., if the water is made relatively more shallow by the accumulation of sand or gravel at their bases, as commonly happens after a time; in such cases the incoming waves are altered into breakers by the sloping bottom that they meet there.

The reflection back of storm seas from a cliff or breakwater against the next incoming waves may so increase the heights and steepness of the latter as to cause them to break heavily, some distance out from the barrier. But the counterwaves may prevent heavy breakers from developing there at all, if the weather is moderate or the wind offshore. It has been stated that small boats can lie in safety in the zone of confused but low wave action that results next to the shore line under these circumstances. We can only comment, in this regard, that we have never seen a situation of this sort, except on a very minor scale and when the waves were so small that they were not dangerous in any case.

Alteration in length and in velocity over a shoaling bottom.—A wave first begins to show measurable deformation when it reaches

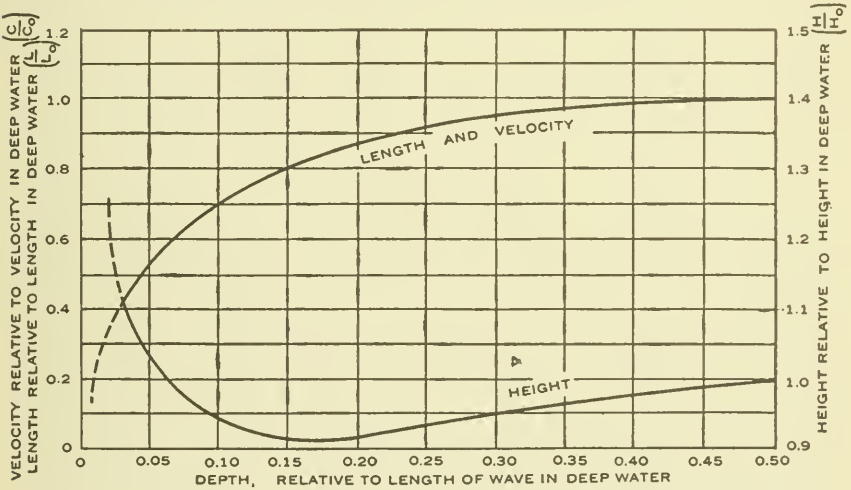

FIGURE 21.—Theoretical alteration in the dimensions of waves as they advance over a shoaling bottom.

a point over a shoaling bottom where the depth of the water (measured below undisturbed sea level) is about one-half the wave length from crest to crest. It has long been known that the lengths of waves are progressively reduced in their further progress from this point onward, so that they are telescoped together, as it were, as they near the shore.

The reduction that takes place in the lengths and in the velocities of waves over a shoaling bottom is usually given as proportional to the square root of the depth of water. Recent observational as well as theoretical studies, however, have shown that the situation is much more complex than this, and especially that the decrease in the length of a wave, and hence the increase in its steepness, is much more abrupt as the wave approaches the shore line than was held by the older

view. It is perhaps of equal interest that the relationship between lengths and velocities that applies to waves in deep water is altered as they run in over a shoaling bottom, with the result that waves that differ widely in length tend to run at similar velocities as they near the breaker line. This is illustrated in figure 21, from which the proportional alteration in length and in velocity of a wave can be read directly at different points in its advance over shoaling bottom. The relationship is also summarized in table 29.

TABLE 29.—*Decrease in lengths and velocities of waves of different dimensions as they advance over a shoaling bottom*

Depth of water (feet)	Waves							
	Length (feet)	Velocity (knots)	Length (feet)	Velocity (knots)	Length (feet)	Velocity (knots)	Length (feet)	Velocity (knots)
Over 500	1,000	42.5	500	30.0	250	21.2	100	13.4
500	1,000	42.5	500	30.0	250	21.2	100	13.4
100	710	30.2	445	26.7	248	21.0	100	13.4
75	635	27.0	410	24.6	240	20.3	100	13.4
50	530	22.5	355	21.3	222	18.9	99	13.3
25	380	16.2	265	15.9	178	15.0	93	12.5
10	240	10.2	170	10.2	120	10.2	71	9.5

Perhaps the most interesting rule illustrated by table 29 is that longer waves are slowed much more, relatively, as they advance shoreward, than shorter ones are, by the time they reach the surf zone. If, for example, this zone were along the 5- or 6-foot contour, as it often is in moderate weather, waves 50 feet long would be still advancing at about 70 percent of their original velocity when they broke, but waves 200 feet long at only about one-fourth the initial velocity, i. e., at about 5 knots. It is for this reason that breakers, caused by a long swell, so often seem to hang almost stationary for the few instants before their crests fall forward.

The fact that waves are slowed down by the effect of the bottom can be used to great advantage in determining water depths off an inaccessible coast. Overlapping aerial photographs are taken at short, accurately known intervals of time. From these, the rate of advance, or velocity, of several wave crests is measured. By applying the relationships between wave velocity, period, and depth of water, the depth is then found.

It is pointed out, on page 32, that the simple relationship between velocity, length, and period holds only for waves that are very low, relative to their lengths, and that steep waves travel a little faster than would be indicated by the simplified equation (See footnote 7, p. 32.) When waves run into shoaling water and steepen further, the increase in their heights seems to oppose their tendency to shorten, the result

being that they run a little faster than might be expected of lower waves of the same length. In extreme cases their velocities may increase in this way by as much as 10 percent, but usually the effect is much less than this.

It is commonly stated that the periods of breakers on the shore are the same as those of the waves out in deeper water, since the reduction in the velocities and in lengths of the latter, over the shoaling bottom, are in at least approximately the same ratio. Any other condition would require either the development of entirely new waves or an accumulation of waves, or the complete disappearance of some of the waves during the last part of their advance shoreward.

On the other hand, it has recently been reported, from observations taken with a special wave meter, working semiautomatically, that the periods of waves advancing over a shoaling bottom usually increase—and by a maximum of 25 percent—but with some of the readings showing a small decrease.[33]

Similarly, the average periods of the waves a short distance offshore were reported shorter by about one-half second than those of the breakers 34 percent of the time, but larger 22 percent of the time, during a series of 38 observations off the island of Martha's Vineyard. And the periods of small breakers, watched by us on another recent occasion, averaged 3 to 4 seconds when the waves half a mile out from the land had averaged only about 25 feet long shortly previous, which corresponds to an average period there of only about 2.25 seconds.

We believe, however, that an explanation for these discrepancies can be found in the conditions under which observations are likely to be made. When there is an old swell, with younger and shorter waves running on top of it, as is often the case, the breakers from the larger waves may swamp out or obscure the smaller ones before these reach the point where they would break. In such cases, the periods would average longer for the breakers than for the waves farther out. On the other hand, when the sea is irregular and confused, some of the waves are likely to be overlooked offshore, even if they do not differ greatly in size; but since they, too, would develop nonetheless into definite breakers, the periods for the latter would be shorter than the apparent periods of the waves farther out. The individual periods of any given run of breakers always differ considerably from one to the next, as do those of the waves offshore, because of the variation in length among the latter. The following tabulation of observations, made recently at South Beach, Martha's Vineyard, may serve as an indication of monthly variations for the northeastern coast of the United States.

[33] Ivanov, A. A. 1938. On the propagation of waves near the coastline. (In Russian.) English summary. Izv. Akad. nauk. ser. geogr. geofiz. pp. 490–491.

Irregularities, however, of the sorts just cited, do not vitiate the underlying rule that the periods of waves that preserve their identity are at least approximately the same when they break as when they are farther out. Consequently, if one times the intervals between successive breakers, as can easily be done on any ordinary watch that has a second hand, one can at least roughly calculate the lengths that these same waves had while they were still out in deep water or vice versa, and many calculations of this sort have been published for various parts of the world. Average periods, for example, of 8 to 12 seconds, for the waves included in table 30, correspond to lengths of about 328 feet to about 737 feet offshore, and an average of 10 seconds between breakers timed by us on the southwest coast of Ceylon, January 1902, corresponds to an average wave length offshore of about 512 feet.

TABLE 30.—*Frequency distribution of waves of different periods at South Beach, Marthas Vineyard, from observations made between January and April 1944. Each case is the mean of 20 consecutive waves*

Month	Mean period in seconds											Monthly mean period (seconds)
	6	7	8	9	10	11	12	13	14	15	16	
January	2	2	15	13	7	11	2	------	1	------	1	9.4
February	------	3	6	5	13	12	7	2	3	------	------	10.4
March	------	5	12	9	12	7	6	1	1	2	------	9.8
April	1	6	16	13	10	2	1	------	------	------	------	8.7
Total cases	3	16	49	40	42	32	16	3	5	2	1	----------
Frequency (percent)	1	8	24	19	20	15	8	1	3	1	1	----------

It is fortunate for anyone planning to land through the surf that the period of a wave does not alter as it nears the land (unless by its union with another), for thanks to this fact, measurements of the periods of waves offshore, which are comparatively easy to make (p. 61), give at least a rough indication of the periods between breakers on a neighboring beach. And this is a matter of some practical importance, for the longer the time interval is between successive breakers, the easier it is to bring a boat in through them, or to go out again from the shore.

Alteration in height over a shoaling bottom.—The most important feature of breakers to anyone who has to land through them is their height. And it has been known to seafarers, doubtless since the days of the Phoenicians, that swells often grow considerably higher just before they break. The most noticeable alteration in their heights as they move in over a shoaling bottom is thus the reverse of what occurs for their lengths and their velocities.

It is not so generally known, because only recently discovered, that this increase in height is preceded by a very small initial decrease, which begins when the depth is about one-half as great as the length

the wave had offshore. The wave regains its initial height when it reaches the point where the depth is about 0.06 as great as its own initial length, after which it becomes higher than the height offshore (fig. 21).[34]

It is the initial length of the wave and not its height that determines at what depth, i. e., at what point over the bottom slope, its shape begins to change. A relatively long wave suffers greater deformation than a relatively short one, because the alteration continues through a greater range of depth in the first case than in the second. Consequently, it is the initial steepness of the wave (i. e., the ratio between its length and its height while still out in deep water) that determines whether the increase in height that follows the initial decrease will more than counterbalance the latter or not and, hence, whether the wave will be appreciably higher at the time it breaks than it was originally. Under most conditions on open coasts, breakers are higher than the waves.

The following example may help to make this clear. Assume two series of waves, both of them 2 feet high out in deep water, but one series 500 feet long, the other only 100 feet. Measurable deformation of the longer waves would commence when they reached a point where the water was still about 250 feet deep. As they advanced shoreward, their heights (after the slight initial decrease) would theoretically increase to 2.1 feet by the time they reached the 20–foot belt, to 2.7 feet by the time they reached a point where the water was about 7 feet deep, and to 3.5 feet at the 5.5–foot line, where a wave of this initial steepness might be expected to break. The shorter waves, however, would continue their progress unaltered until they reached a point where the depth was 40 feet, would decrease to a height of only about 1.8 feet by the time they reached the 15–foot line, would then build up again to the original height of 2 feet by the time they reached the 5–foot line, and to 2.3 feet at the 3–foot line, where they might be expected to break.

[34] The change in wave height is brought about by two opposing actions which may be represented in an equation $H = H_o\sqrt{\frac{1}{2}\frac{1}{n}\frac{1}{C/C_o}}$ where H is the height at the selected point in shallow water, H_o is the height in deep water, C and C_o are corresponding values of wave velocity, and n is a complicated function of depth and wave length:

$$n = \frac{1}{2}\left[1 + \frac{4\pi\left(\frac{d}{L}\right)}{\sinh\left(4\pi\frac{d}{L}\right)}\right]$$

where d is the depth of water, and L is the wave length in deep water. The first action tends to decrease the wave height by making the value of n increase. But meantime the wave velocity and hence wave length is decreasing, which causes the crests to peak up. As shown in the equation, when C/C_o decreases the relative wave height must increase. The resulting effect of the two opposing actions, therefore, is to cause a small initial decrease in the height followed by a rapid increase, until the wave becomes unstable and breaks. The initial decrease, first theoretically predicted (O'Brien and others. 1942. Techn. rep. U. S. Beach Erosion Board. No. 2. pp. 35–37) has been confirmed by tank experiments and also by observations at the Scripps and Woods Hole Institutions.

In general, waves that are less than 10 to 15 times as long out in deep water as they are high, are only about as high when they break as they were offshore. But relatively longer waves may increase considerably in height. At South Beach, Marthas Vineyard, for example, the ratio at the 30–foot contour, and at the time of breaking, between the measured heights for waves of different degrees of steepness has ranged between 1 : 1 and 1 : 2.2, while ratios of 1 : 1.1 to 1 : 1.9 have been recorded at La Jolla, California, between waves offshore and the breakers caused by them. And the increase in height may be considerably greater yet in the cases of very long swells; in fact, an old swell that is relatively so low out over deep water as to be hardly perceptible, but very long, may mount to such a height during the last few yards of its advance as to cause a dangerous surf, even in calm weather. And it is during calm or moderate weather that the height of surf is chiefly of importance in landing operations.

It is much easier to measure the periods of waves than to measure their lengths. The alteration in height on a gently sloping bottom is therefore summarized in table 31 for waves of representative sizes, according to their periods.

TABLE 31.—*Heights (to the nearest foot) attained by waves, of different initial heights and periods, at various depths on a gently sloping bottom. Blank spaces indicate that the waves would, in all likelihood, have broken in deeper water, or that waves of the stated shapes could not exist. This table is derived from figure 21 and is based upon theoretical studies, substantiated by measurements of waves taken at the Scripps Institution of Oceanography and at the Woods Hole Oceanographic Institution*

Initial height of wave (feet)	Period of wave (seconds)	Depth of water (feet)					
		30	25	20	15	10	5
4	4	4	4	4	4	4	4
	6	4	4	4	4	4	5
	8	4	4	4	4	5	
	10	4	4	4	5	5	
	12	4	4	4	5	5	
	14	4	4	5	5	6	
	16	5	5	5	5	6	
6	4	6	6	6	5	5	
	6	5	4	6	6	6	
	8	6	6	6	6	7	
	10	6	6	6	7	7	
	12	7	7	7	7	8	
	14	7	7	7	8		
	16	7	7	8	8		
12	4	12	11	11	11		
	6	11	11	11	11		
	8	11	12	12	12		
	10	12	12	13			
	12	13	13	14			
	14	13	14	15			
	16	14	15				
20	4						
	6	18	18				
	8	19					
	10	20					
	12	21					
	14						
	16						

It appears, from published observations, that the height of the surf may even be several times the preceding height of the waves in

special situations where the slope of the bottom steepens very abruptly from deeper water, as in the case of cliffs and of breakwaters. Masses of water may then spout high into the air, or up on the shore, as happens frequently against isolated rocky islands or ledges, along the steeper parts of the offshore faces of coral reefs, against lighthouses, against breakwaters, over submerged ledges, and also against the nearly vertical walls of the antarctic ice barrier, where the depth of the water may be measured in hundreds of fathoms. In fact, it is not unusual for sheets of water—not just foam—to spout more than a hundred feet into the air under such circumstances (for examples, see page 120).

Alteration in steepness.—A wave advancing into shoal water not only becomes steeper as a consequence of its decrease in length, combined in most cases with an increase in height, but it does so very abruptly just before it finally breaks. Anyone who has occasion to come in through the surf in a small boat has this fact impressed upon him, for his boat, which may merely rise and fall bodily with the longer swell offshore, is pitched up more and more steeply as it rides in on the back of a chosen roller, until her bow may be lifted far above her stern just before the breaker develops. This point is discussed in further detail on page 110.

Alteration in the orbital velocities of the water particles.—The orbits around which the water particles move are circles in deep water, but become elliptical, with their larger axis horizontal, when a wave runs into water shoaler than one-half its own initial length (p. 00, fig. 3), and the ellipses become more and more flattened as the water shoals, until the water particles in contact with the bottom simply move to and fro in straight lines. The velocity at which the water particles move around their orbits—uniform while these are circular—is no longer so after they are transformed into ellipses, but is greatest near the crest and the trough. This discrepancy between the velocities along different parts of the elliptical orbits increases as the eccentricity of the orbits increases with the advance of the wave into shoaler and shoaler water, for it is proportional to the length of the major (horizontal) axis of the ellipse.[35] And since the transformation of the orbits from circles to ellipses consists in an expansion of their horizontal axes, with their vertical axes changing only as much as the height of the wave, the velocity with which the water particles advance in the crests and recede in the troughs grows greater and greater as the wave advances into shoaler and shoaler water. The orbital velocities, for example, in the crests and troughs of a wave 15 times as

[35] According to the equation $V''=\frac{2\pi a'}{T}$ where V'' is the orbital velocity along the part of the ellipse where it is at its maximum, a' the half-length of the major axis of the ellipse, and T the period of the wave.

long as high should, theoretically, be almost twice as great when it reached the point where the depth was one-tenth as great as its own initial length (and where it might be expected to break) as they were to begin with. And the longer the wave, relative to its initial height, the greater is the increase that takes place, in this way, in the horizontal velocities of its water particles. (This summary has been drawn from Gaillard, 1904, pp. 41, 97, 135–136, pls. 1 and 5.) The water particles at the crest of a wave may thus be moving forward several times as fast, when it is about to break, as they were originally.

The question of the orbital velocities at the top of the crest at the instant of breaking has not received as much attention as it deserves from a practical standpoint. But anyone who has had experience in surf knows that any object, such as a plank or a small boat floating on the top of a roller, may be swept forward with astonishing rapidity just as the top of the crest falls forward, if the breakers are of the plunging type (p. 111). And this is one of the reasons why it is so difficult to bring even a surfboat in through high breakers, for it is likely to be carried forward over the crest unless it is well handled, to be pitched down bow foremost into the trough ahead, where it will be in imminent danger of broaching to, as its stern continues to be swept forward in the air, or at the least of filling with the water that pours down upon it from above. Surf running of this sort should never be attempted in small boats, except as a last resort.

THE CHARACTERISTICS OF BREAKERS

The breaking of waves out in deep water appears to be caused chiefly by the pressure of the wind, which forces the backs of their crests ahead faster than their leeward sides are advancing, until they come to overhang the troughs. As a rule, it is only the very top of the crest that falls over. Typical breakers on the beach, however, are not caused directly by the wind (although the wind may aid in their formation, if it is blowing strongly onshore), but by the alteration of the wave forms that takes place over shoaling bottom, as described above, by which the waves grow steeper, until they become unstable. It is commonly stated that it is the friction with the bottom that causes this alteration in shape by retarding the lower part of the wave, while the upper part continues to advance. But experimental studies of waves have failed to show that a frictional effect is of importance. Neither is the developing profile of a breaker what it should be if friction were the sole cause, for its front becomes hollowed as the crest steepens, suggesting, rather, that it is a deficiency of water on the front side that causes the crest to overhang the trough in front of it, and consequently to fall forward.

The breakers that develop over evenly sloping beaches are of two chief types, if the wind is not strong enough to interfere with what may be termed their "normal" development. In the one type, the back of the wave continues well rounded up to the instant of breaking (Figs. 22 and 23), whereas its front may become so deeply hollowed that a swimmer, standing on the beach directly in its path and ready to dive through it, may be able to look up for an instant through a sheet of overhanging water, before his head is submerged. The wave forms are very greatly reduced in the act of breaking when the breakers are of this type, which may be named "plunging." And the event occupies only a few seconds—unless, indeed, the wave is coming in at

FIGURE 22.—A breaker of the plunging type, on the coast of New Jersey, showing different stages of development along different parts of the crest. (Woods Hole Oceanographic Institution photograph.)

an angle with the shore, in which case it begins to break first at its inshore end, and does so progressively outward along its crest as the latter continues to advance, as is illustrated by the aerial photograph reproduced in figure 24. In breakers of the second type, the backs of the crests, as well as the fronts, become concave as they near the breaking point, so that they more nearly resemble the profile of the steepest possible wave (fig. 25), a shape known technically as "cycloid."

When the tops of their crests final rise to the angle of instability they do not simply fall forward as do the "plunging" type, but they break continuously (but only along their very tops) as they advance, gradually losing in height by the loss of water from their crests as they near the shore. These may be termed the "spilling" type.

We were fortunate to be in a position to watch the development of both these types of breakers on a recent occasion, while looking out

over a gently sloping beach from a rocky promontory. An old swell was heaving in, the individual members of which were so low that they were not recognizable offshore but which grew to heights of 1½ to 3 feet at the breaker line. Those that rose the highest were of the plunging type, but the smaller ones were of the spilling type, and in many cases one part of a single wave crest developed as the one type, another part as the other; or a "spilling" breaker might either follow or precede a "plunging" one.

FIGURE 23.—Oblique view of a breaker of the plunging type on the coast of New Jersey. (Woods Hole Oceanographic Institution photograph.)

Long, gentle swells—initial steepness (H : L) less than 0.005—commonly produce breakers of the plunging type, especially when the wind is blowing offshore, while waves that are less than 100 times as long, offshore, as they are high, often produce breakers of the spilling type, especially when the wind is blowing onshore. But individual

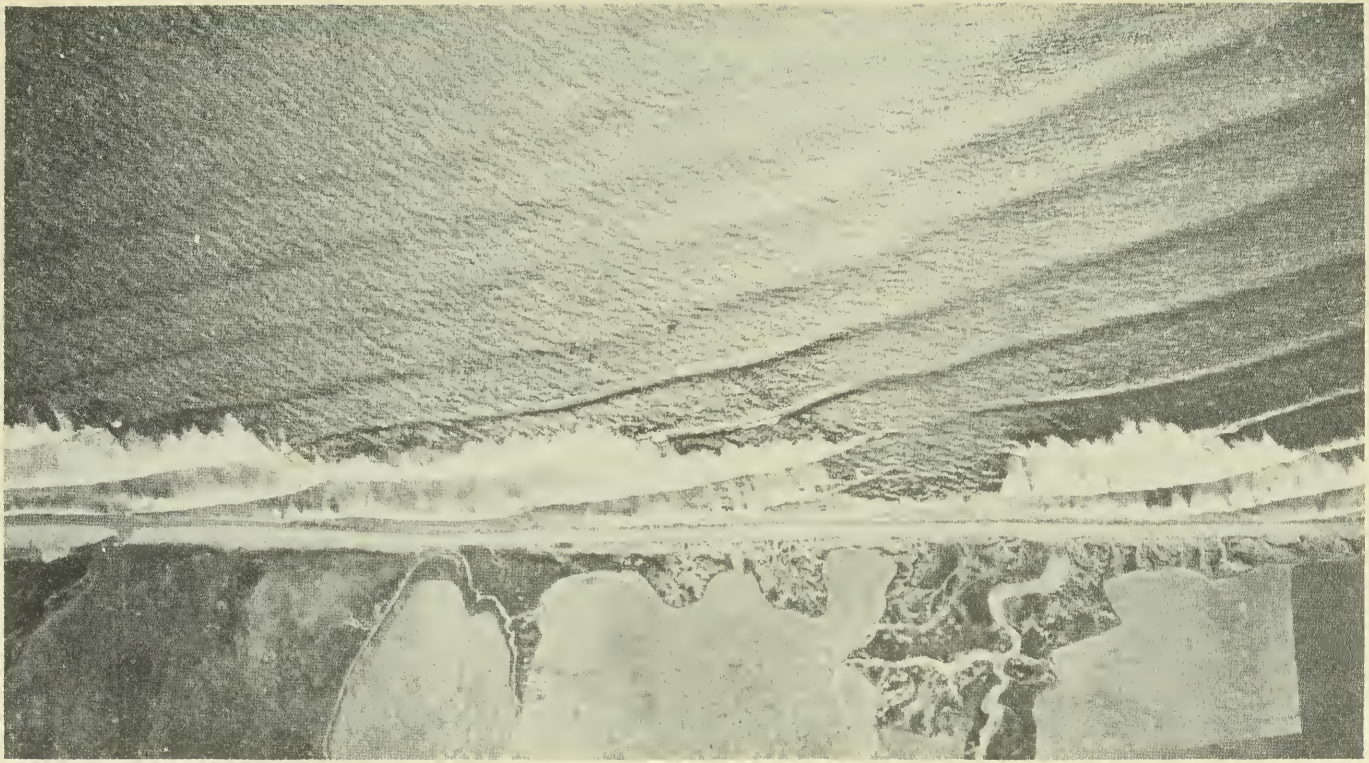

FIGURE 24.—Aerial photograph of breakers of the plunging type, about 3 feet high, breaking obliquely on the beach at Oceanside, California. (Official U. S. Navy photograph.)

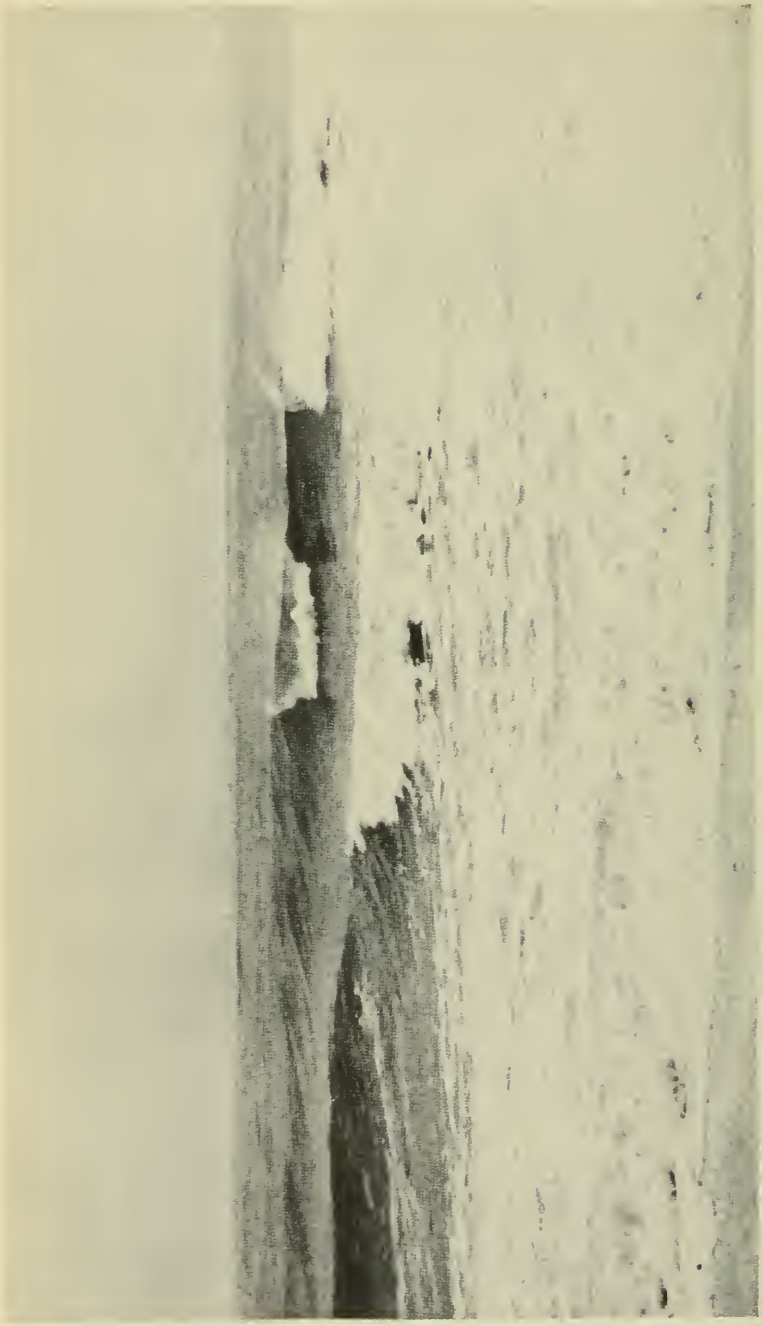

FIGURE 25.—A breaker of the spilling type, preceding one of the plunging type, on the outer coast of Cape Cod.
(U. S. Coast Guard photograph.)

breakers may share the characteristics of both the plunging and of the spilling types, for while they resemble the former in their general development, the break does not involve enough of the crest to lower the wave form much (fig. 26). The wave then steepens again in its further advance up the shoaling bottom, breaks partially for a second time, and sometimes for even a third or a fourth time. Breakers of this sort may be termed "intermittent"; they are seen very commonly during onshore storms.

WAVES OF TRANSLATION

In this connection, it is necessary to mention a very different sort of wave that develops when a wave breaks some distance out, whether on a gently sloping bottom or over the seaward margin of a submarine terrace, for the mass of water that falls forward from it, and that is suddenly added to the comparatively level water surface in advance of it, often sets up a secondary wave of permanent form. Such a wave consists of a crest with precipitous foaming front, and without any trough, so that the water particles all move forward together—hence its name, "wave of translation" (fig. 27). But it seems that the foaming crests of this sort commonly seen almost always represent a combination between these waves of translation and whatever remnants of the original wave may still persist, for it is often easy to see that the general advance of the bits of foam is combined with an oscillating movement, forward and back. On a calm day there may be anywhere from 1 to 4 or 5 lines of these combined crests, decreasing in size shoreward, between the innermost heavy breaker and the beach. And they may advance, unaltered, as a secondary, low surf for long distances, perhaps for as much as a mile if the slope is gentle. They are very characteristic in appearance, flat-topped, and with the distances between them many times longer than their own heights.

When the form of a wave is largely destroyed in the process of breaking, as it often is with a long swell in moderate weather, the only other breaking waves between it and the beach may be one to several lines of these small crests. But when the undulatory motion of a wave continues after it first breaks, the combination between it and the waves of translation it produces may cause secondary breakers several feet high, though never so large as the primary breakers farther out.

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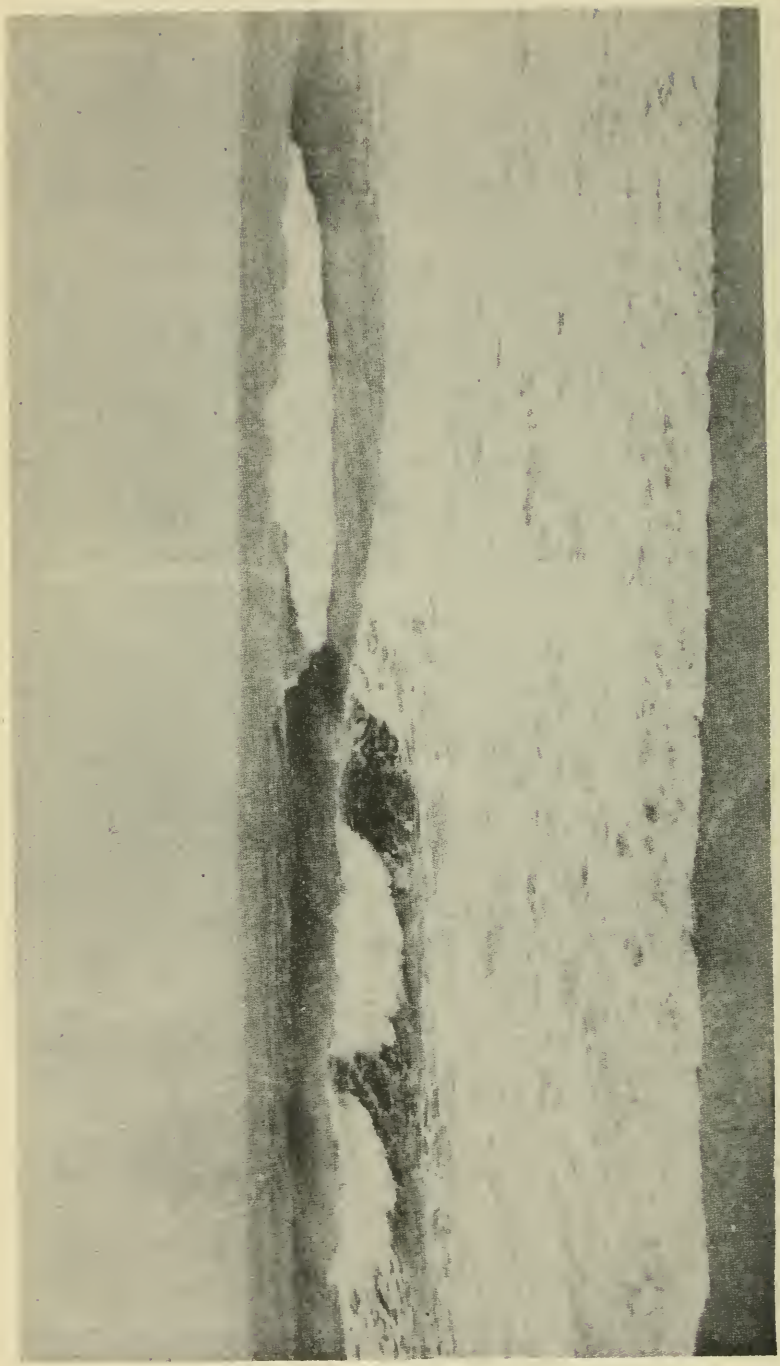

FIGURE 26.—A breaker, intermediate between the plunging and spilling types, preceding another of the plunging type. Outer coast of Cape Cod. (U. S. Coast Guard photograph.)

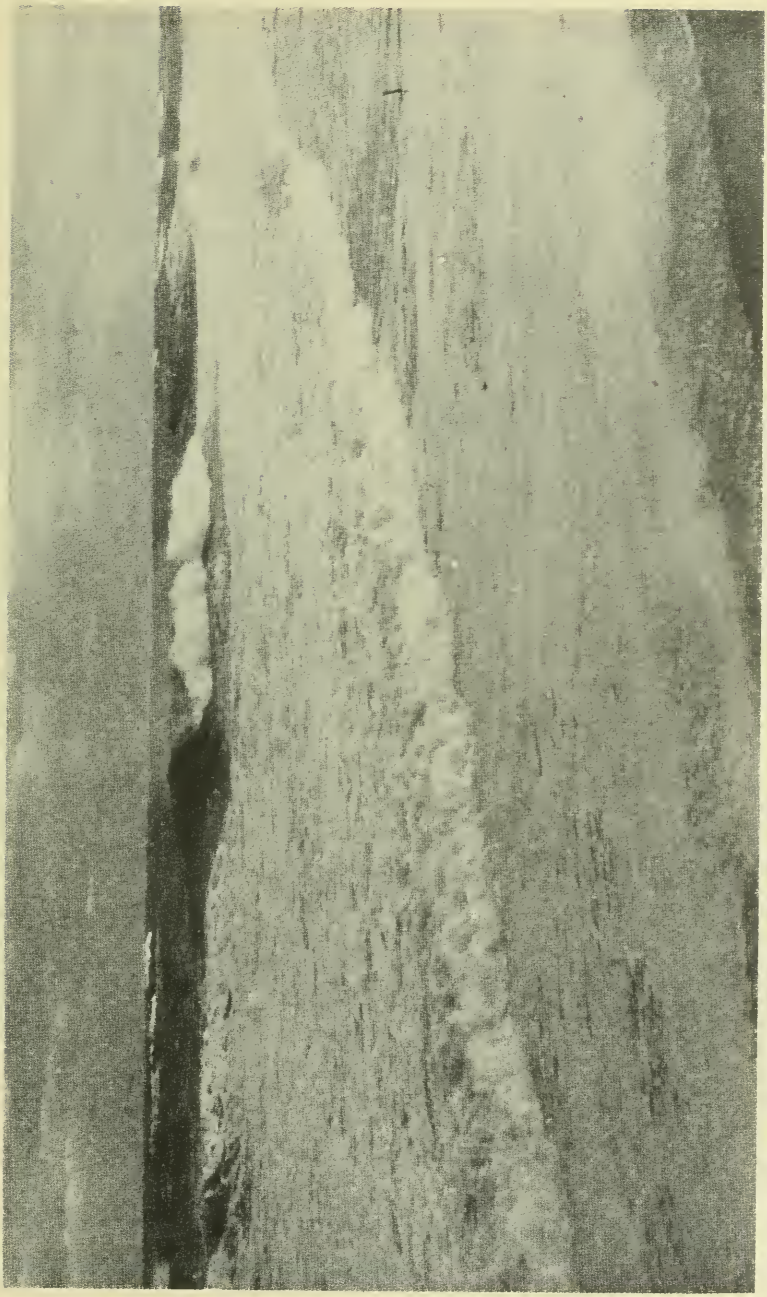

FIGURE 27.—The foaming crest of a well-developed wave of translation preceding a breaker up a gently sloping beach on the outer coast of Cape Cod. (Woods-Hole Oceanographic Institution photograph.)

Chapter 7

THE CHARACTER OF SURF UNDER DIFFERENT CONDITIONS

The character of the breakers that will develop at any particular place on the coast, at any particular time, for waves of given heights and lengths—or even whether there will be any breakers at all—depends on local factors. Among these the general contour of the bottom, the presence or absence of obstructions offshore, the nature of the coast, the stage of the tide, the strengths and directions of currents, and the direction and strength of the wind all play their parts.

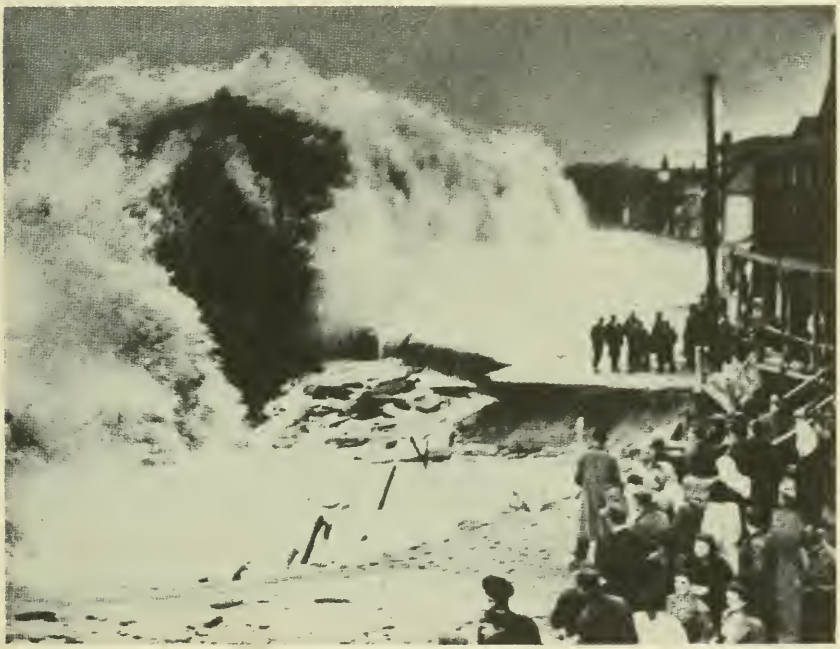

FIGURE 28.—The heavy surf of November 22, 1944, at Winthrop, Massachusetts, beating against the water front boulevard to which it has done great damage. (Photograph, courtesy of Edward R. Snow.)

THE HEIGHT OF SURF

Rough estimates of the heights of breakers are apt to be too high, so impressive a spectacle is a heavy surf. It is also important to distinguish between the heights of the actual wave forms at the instant of breaking and the height in the air to which sheets of water may be cast when surf beats against steep ledges, sea walls, cliffs, or breakwaters, for the breakers may spout to almost unbelievable heights in severe storms in situations of these sorts (fig. 28). And

it is these that have been stressed the most often in published accounts, because of their importance from an engineering standpoint.

In severe easterly gales, for example, masses of water sometimes entirely envelop Minot's Lighthouse, a 97-foot tower standing on an off-lying ledge in the southern side of Massachusetts Bay (fig. 29); we have seen it do so, ourselves. The bell has been broken loose by the surf at a height of about 100 feet above sea level at the Bishop's Rock

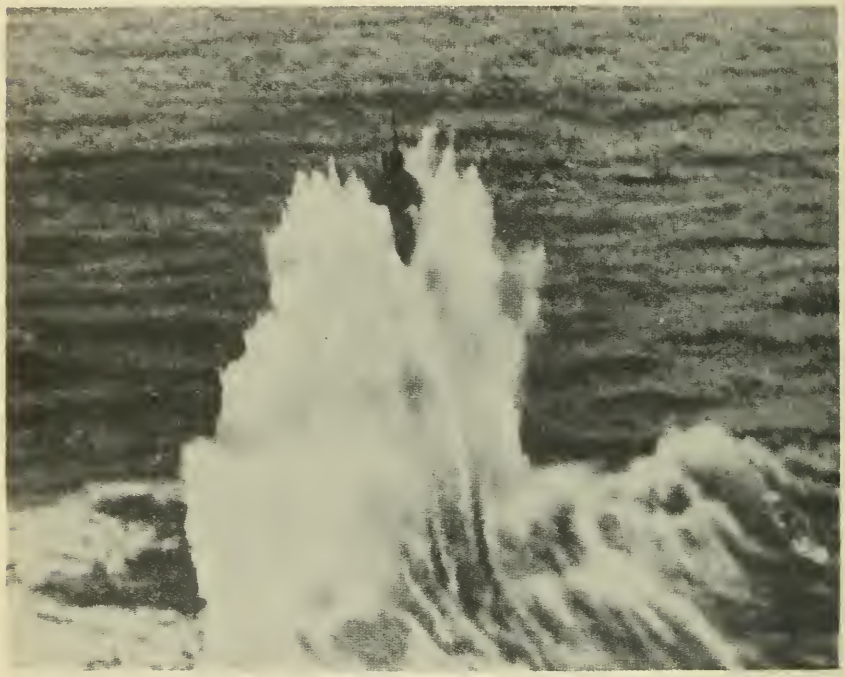

FIGURE 29.—Aerial photograph showing the surf almost wholly enveloping Minot's Light, Massachusetts, during the gale of January 12, 1941. (Photograph, courtesy of Edward R. Snow.)

Light, England; the light tower has been broken in at an elevation of 195 feet on the Island of Uist in the Shetlands; the glass in the lamp has been struck at an elevation of 158 feet at Tillamook Rock Lighthouse on the coast of Oregon, where on February 11, 1902, water from the surf fell back in solid masses upon the roof of the dwelling at a height of 200 feet above the sea. (See Johnson, 1919, for a long list of happenings of this sort.) And we, ourselves, from the United States Fisheries steamer *Albatross*, December 14, 1904, saw the surf from a low swell, topped by a moderate sea, breaking right over the lower parts of the islet Sala y Gomez, in the southeastern Pacific, with sheets of spray flying even over its highest parts, some 80 feet above sea level. Spray spouting upward over steep submerged ledges is also

a common spectacle off many coasts, but spouting takes place off beaches only when breakers come together. Surf of this sort is not of immediate concern as regards landing operations in any case, because no one in his senses would attempt to come in through the breakers under the conditions of wind and weather and of coast, under which it develops.

In general, the height of the breakers depends on the height and steepness of the waves offshore, as shown in table 32. The steeper the waves in deep water, the less will be their proportionate increase in height before breaking. The average relationship is shown in table 33, but it must be noted that observations may vary by 25 percent. Moreover, very steep waves may break while the height is still less than the original height.

TABLE 32.—*The approximate heights at breaking (boldface) and the ranges of depths at which breaking occurs (italic) for waves of different dimensions. It is assumed that the waves break where the depth is from 1.3 to 2 times the wave height at that instant. The heights at breaking are based on studies made at the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution*

Period of wave (seconds)	Wave length offshore (feet)	Initial wave height (feet)						
		4	6	8	10	12	16	20
4	82	**4** *5-8*	**6** *8-12*	**8** *10-16*	**10** *13-20*	**12** *16-24*	----	----
6	184	**5** *6-10*	**6** *8-12*	**8** *10-16*	**10** *13-20*	**12** *16-24*	**16** *21-32*	**20** *26-40*
8	328	**5** *6-10*	**7** *9-14*	**9** *12-18*	**11** *14-22*	**13** *27-26*	**17** *22-34*	**20** *26-40*
10	512	**6** *8-12*	**8** *10-16*	**10** *13-20*	**12** *16-24*	**14** *18-28*	**18** *23-36*	**21** *27-42*
12	738	**6** *8-12*	**9** *12-18*	**11** *14-22*	**13** *17-26*	**15** *19-30*	**19** *25-38*	**22** *29-44*
14	1,003	**7** *9-14*	**10** *13-20*	**12** *16-24*	**14** *18-28*	**16** *21-32*	**19** *25-38*	**24** *31-48*
16	1,310	**8** *10-16*	**10** *13-20*	**13** *17-26*	**15** *19-30*	**17** *22-34*	**20** *26-40*	**25** *32-50*

TABLE 33.—*Ratio of breaker height to offshore height for waves of different degrees of steepness in deep water*

Ratio between length and height of wave in deep water	Ratio between breaker height and height of wave in deep water
20:1	1.0:1
40:1	1.2:1
100:1	1.4:1
125:1	1.6:1

Waves that are 6 to 8 feet high out at sea—a common height in moderate weather—are only of about this same height when they break on the shore, if their ratio of length to height offshore is small. Storm waves, say 15 to 20 feet high offshore, are likely to cause a surf at least 18 to 22 feet high, if their crests are parallel to the coast, though

somewhat lower if they are coming in at an angle, because of their refraction (as explained on p. 157). And high breakers are also often caused by old swells, for while these are often much lower than the storm waves that engendered them, they are so much longer that they begin to pile up in much deeper water than would a storm wave of equal height. Thus, a swell that was 1,500 feet long (period of about 17 seconds) and 5 feet high would produce a 10-foot surf; and it is not unusual for old swells to produce breakers more than twice as high as their own deep water heights, for this reason.

The breakers that form in moderate weather are ordinarily highest at the instant that the overfall takes place, with the precise heights governed chiefly by how high the parent waves are over deeper water offshore, as compared with their lengths there, i. e., on their initial steepness. And since waves vary almost infinitely in their lengths and heights offshore, surf exhibits a corresponding range, from only an inch or two high up to the heights of the largest storm waves. Breakers have, for example, been measured from 2 inches up to 7 feet in height at St. Augustine, Florida (Gaillard, 1904, p. 33); from a few inches up to about 13 feet at South Beach, Martha's Vineyard; and from 1½ feet up to 20 feet or so on the coast of Morocco (p. 69), after the establishment of a swell that was fairly consistent in period for a number of hours.

Some records of high surf, culled from available data, are the following:

a. Rollers 12 to 20 feet high have been observed at the Island of Ascension, at the 10-fathom line, during a period of violent surf that was probably somewhat higher than this, because produced by a swell.[36]

b. The heavy swells that run in from storms at sea are described as breaking about 20 feet high against the coral reefs of the Hawaiian Islands.[37]

c. Near Peterhead, Scotland, measured waves that were 26 feet high and 500 feet long in 7 to 8 fathoms crested and broke along the 5½-fathom line, by which time they may be assumed to have attained a height well over 26 feet.

d. At Algoa Bay, South Africa, unbroken waves, measured from a staging, were 21 feet high close in to the breaking line, where the depth of water was 23 feet, indicating a deepwater height of perhaps 17 or 18 feet.

e. Breakers which damaged the breakwater at Wick Bay, Scotland, were estimated by the resident engineer to have a maximum height of 42 feet.

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[36] Buchanan, J. Y. 1888. The exploration of the Gulf of Guinea. Scott. geogr. mag., vol. 4, p. 235.

[37] Blake, Tom. 1935. Hawaiian surf board, Honolulu, Paradise of the Pacific Press, p. 63.

This last instance is the greatest breaker height that we have found recorded in print. But we have no doubt that breakers are sometimes as high as this on the Pacific coast of the United States from northern California to the Straits of Juan de Fuca, where the surf is as heavy as it is anywhere in the world, to judge from the very considerable depths over which it develops there during the stormy season. Thus sea captains of long experience, and local residents, as well as members of the United States Army Corps of Engineers, of the United States Coast and Geodetic Survey, of the United States Lighthouse Service, and of the United States Revenue Marine Service (the two latter services have since been incorporated in the United States Coast Guard) have reported breakers in depths as great as 42 to 54 feet, and perhaps even to 60 feet on the San Francisco Bar; at 56 to 57 feet at Cape Mendocino, California; commonly at 42 to 45 feet, sometimes at 60 feet on the Columbia River Bar during severe onshore gales; and at 42 to 60 feet at various points along the coasts of Oregon and Washington (for further references to these instances, and to their source, see p. 126). Assuming that the heights of the breakers averaged about one-half to two-thirds as great as the depth of water where the surf developed, a ratio usual when the wind is blowing strongly onshore (p. 130), the foregoing instances suggest a surf commonly 21 to 35 feet high in stormy weather, occasionally 30 to 40 feet high, and perhaps even as high as 45 feet during the most severe gales. And surf no doubt as high, because breaking at depths equally great, has also been reported in the North Sea off the coast of Holland, off the Guianas, and along Yucatan in the Caribbean, as well as in other parts of the world (p. 127).

In localities where the state of the sea depends chiefly on the wind distribution nearby, and where long swells traveling from afar are unusual, the surf is usually highest when the wind is strong onshore, as might be expected, and very low or nonexistent otherwise. And the height of the breakers in stormy weather is governed by the effective fetch at the time. The surf, for example, is seldom more than 12 to 15 feet high anywhere along the beaches of the northeastern United States, because it is very unusual for a strong easterly wind to blow (and to persist) over any fixed area of large extent in middle or high latitudes of the western North Atlantic. But a heavy surf may develop, during periods of calm, from old swells on coasts remote from stormy regions, or even during periods of offshore wind, if these are not too strong. Thus Wallace [38] wrote, that at the harbor of Ampanan, on Lombok, in the East Indies "Where we lay anchored, about a quarter of a mile from the shore, not the slightest swell was perceptible, but on approaching nearer undulations began, which

[38] Wallace, A. R. 1869. Malay Archipelago, vol. 1, p. 228.

rapidly increased, so as to form rollers which toppled over on the beach at regular intervals with a noise like thunder. Sometimes this surf increases suddenly during perfect calms, to as great a force and fury as when a gale of wind is blowing." A moderately heavy surf also develops, similarly, from time to time on the coast of Peru in calm weather, as described many years ago by Humboldt, who observed breakers 10 to 14 feet high at Callao, on such occasions.[39] And we can assure the reader that it is no less spectacular a sight now than it was then, as one looks out over the sea, to watch the swells, so small as to be imperceptible offshore, being reborn, as it were, over the shoaling bottom in glassy calm weather, and then increasing in height, without apparent cause, until they break.

Two examples in the development of breakers of moderate size from a swell so low offshore that the photographs give no hint of its existence to seaward of the breaker line are pictured in figure 30. Nor is it unusual for the breakers that form in this way to be of the same general order of magnitude as the seas are that break out over deep water in windy weather, i. e., as high as 6 to 20 feet, and sometimes even higher. The surf that so constantly pounds the exposed faces of coral reefs and islands in the western tropical Pacific and Indian oceans, even in calm weather, are cases in point.

The individual breakers that compose a surf always vary considerably in height as they succeed one another. Thus it has been estimated that the heights of the breakers on the Californian beaches usually vary between two-thirds and four-thirds of their mean heights, which probably applies to breakers from swells in general. And our own observations suggest that the variation is often wider still for breakers caused by storm seas. These variations are due in part to the fact that the individual members of any train of waves always differ more or less both in height and in initial steepness, one from the next, partly because it is a common event in a storm for a train of waves to come considerably larger than the common run (p. 00), and also because two or more waves, or series of waves, ofen unite before they reach the surf zone, whether advancing in the same direction or coming from different directions, so that a breaker or series of breakers much larger than the others may come at intervals. One of 15 feet, observed at Long Branch, New Jersey, February 8, 1944, when the average height during a 10-minute interval was only 4 feet, may have had this origin. And while there is no foundation for the old notion that every seventh or every ninth breaker is invariably the largest, experienced surfmen are well acquainted with the fact that an unpredictable single huge breaker, or a series of such, may develop on days when the general run are low, or of only moderate heights,

[39] Humboldt, A. von. 1858. Kosmos, Stuttgart. vol. 4, p. 229.

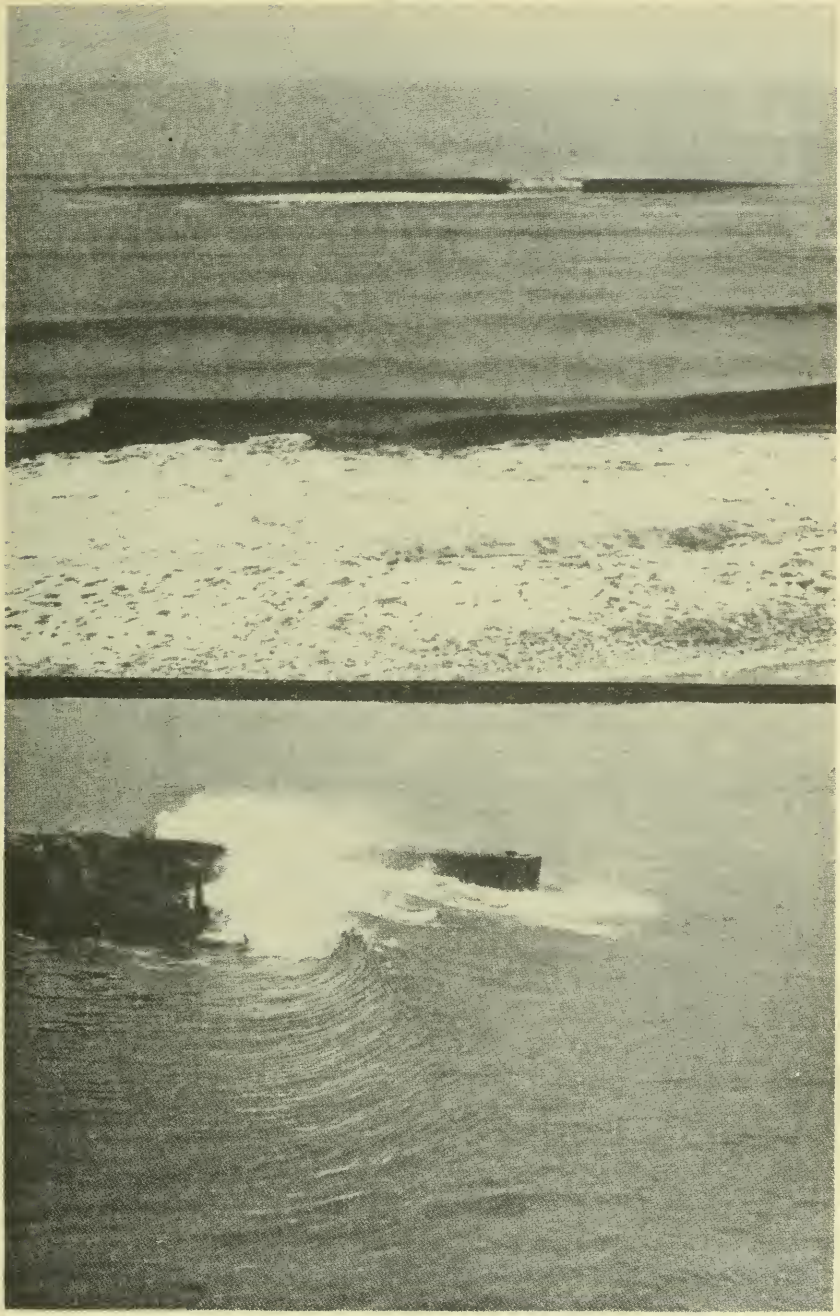

FIGURE 30.—Breakers rising 5 to 6 feet high over a bar along the south shore of Long Island, New York, above), and running along a stone pier on the coast of New Jersey (below). In both cases, the breakers are caused by swells so low that they are hardly visible offshore. (U. S. Coast Guard photograph.)

and take advantage of the series of smaller breakers that succeed a series of larger ones, when coming in to land. A cross sea also renders the surf much worse than it would be otherwise, partly because it disturbs the regularity of the wave pattern, but especially because steep peaks may shoot upward along the breaker zone, when waves coming from different directions chance to join just before breaking, as happens offshore under similar conditions (p. 124). The resulting surf may be so high and so confused that any attempt to land through it would be much more dangerous than an observer offshore would expect, if he did not detect the presence of the opposing trains of waves.

DEPTH OF WATER IN WHICH SURF DEVELOPS

Waves of moderate steepness, generated in deep water, but then advancing over a shoaling bottom in calm weather, have been found from tank experiments and from field observations on the coast of California to break when they reach the point where the depth is no longer more than about 1.3 times as great as their own heights there, which is close to the theoretical expectation. But common experience in various localities is that the ratio between height of breaker and depth of water where it breaks varies considerably, under different conditions of wind, sea, and current (if there is any).

Thus, the surf at St. Augustine, Fla., has been seen breaking where the depth was only about 0.72 as great as the height of the breakers in some cases, but where the depth was twice as great as the heights of the breakers in others (Gaillard, 1904, p. 120). Measured waves have also been seen to break in depths ranging from 1.3 to 1.7 times as great as their own heights at South Beach, Martha's Vineyard; in depths 1 to 2.7 times their heights on Lake Superior (Gaillard, 1904, pp. 121–122); and in depths of from 0.9 to 2.0 as great as their own heights at La Jolla, California. Measured waves that were 26 feet high at the 7 or 8-fathom line have been seen breaking at the 5½-fathom line (i. e., in 33 feet of water) at Peterhead, Scotland; swells 5.5 to 8 feet high have been seen breaking where the depth was 2.2 to 2.3 times as great as that at Scarboro, England; and ground swells 10 to 12 feet high break commonly where the general low tide depth is about 10 fathoms (60 feet) on Riy Bank off South Africa, sometimes for days at a time. Other striking cases of breakers in water considerably deeper than the probable heights of the waves at the time are the surf often reported at depths of 7 to 9 fathoms (42 to 54 feet), and sometimes to 10 fathoms (60 feet) on San Francisco Bar, and on the Columbia River Bar; at 90 feet at Cape Foulweather, Oregon; at 48 feet off Port Orford, Oregon; at 42 to 48 feet between Trinidad and Pilot

Rock, Oregon; and at 48 to 60 feet near Yaquina and Coos Bays, Oregon. Surf has also been reported over depths as great as 72 feet along the Washington coast, and even at 90 feet there in the most severe weather,[40] as it also has in the southern part of the North Sea, where the seas break heavily over Borkum Ridge in depths of 10 to 15 fathoms (60 to 90 feet) during onshore gales. Surf has been recorded at depths of 50 to 56 feet off the coasts of the Guianas; at 56 to 66 feet off Yucatan; at 66 to 100 feet around Madeira; at 66 to 77 feet off Algeria; also at 80 feet off northern Spain, although a conflict between waves and currents may perhaps have been responsible for some of these extreme cases (p. 51).

The instances cited are enough to show that the statement, often made, that a wave may be expected to break where the depth is equal to its own height is not an adequate one; nor does this even apply to the common run of surf. The range of variation which may be expected with waves of different sizes is shown in table 32. The chief reason for the very considerable variation that has actually been observed in the ratio between height of surf and depth of water is that waves tend to break in somewhat deeper water with a strong onshore wind than they do in moderate weather, because the direct pressure of the wind against the windward sides of their crests increases the steepness of the latter, thus hastening their overfall. Thus waves, advancing over a bottom slope of 1 in 100, off St. Augustine, Fla., have been described as breaking where the depth was 1.25 times as great as their own heights with a strong onshore wind, though they did not do so in calm weather until they reached the point where the depth was equal to their own heights at the moment.

It also appears, from various observations, that waves of equal lengths and heights break in considerably deeper water where the slope of the bottom changes abruptly than when they run in over a uniform slope. Thus, waves may perhaps break where the depth averages about 1.7 to 1.8 as great as the breaker height, where a steep bottom slope is followed by a more gentle one, if the weather is calm and if there is no current. This probably is the explanation for the broken water that is often to be seen along the offshore edges of shoals and of reefs, over depths greater than those at which surf would otherwise be expected with waves of the sizes running at the time.

The interference that often develops between trains of waves coming from different directions, also may increase their heights and the steepness of the individual crests, not only causing these to break in considerably deeper water than would happen otherwise, but rendering the breakers so much more complex in pattern, as greatly to increase

[40] The information as to the depth of which surf breaks along the northwest coast of the United States is abstracted from a summary by Gaillard, 1904, pp. 115–117.

the danger of landing if they are more than a few feet high. A very striking example of the geometric nature of the patterns that are produced on shelving beaches in this way, when small breakers come together from different directions is pictured in figure 31. A current (tidal or other) flowing against the wind will also tend to cause waves to break in water deeper than would otherwise be the case, as illustrated by the aerial photograph reproduced in figure 32, for when a wave meets an opposing current it is not only steepened, but its height is increased as described on p. 53. A strong current may, in fact, be as effective as a shoal or bar in causing large breakers to develop well

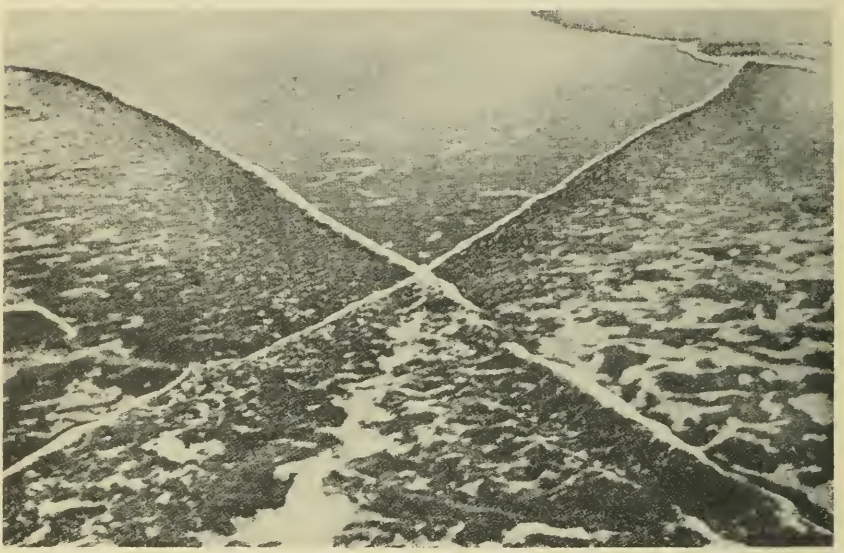

FIGURE 31.—Geometric pattern produced by low breakers crossing each other from different directions on the English coast. (After Cornish, courtesy of Macmillan Co. and Cambridge University Press.)

out from the land. The frequent reports of breakers over deeply submerged banks, or along the slopes of such, are thus explained, for example, along the Newfoundland Banks, off Ireland, and at the mouth of the English Channel where the depth is something like 100 fathoms.

Waves have also been reported as breaking in deeper water, if running in over a steeply sloping bottom, than is usual off more gently sloping beaches. The ratio of breaking depth to height of wave in calm weather has been described, for example, as twice as large over a 1 in 12 slope as a 1 in 100 slope at St. Augustine, Florida (Gaillard, 1904, p. 120). On the other hand, the results of laboratory experiments on a rather limited range of slopes do not support the view that the steepness of the slope of the bottom has any great importance in this

FIGURE 32.—Aerial photograph showing waves breaking much farther out at the mouth of a tidal inlet, on the New Jersey coast, than on the neighboring beach. (U. S. Navy photograph.)

respect within the range that has been investigated, so this question must be regarded as an open one, for the time being.

It is well known that when an offshore wind develops, the surf does not break until closer in to land (i. e., until in shallower water) than when the wind is onshore, or when it is calm. No doubt this is because a head wind tends to delay the steepening of the crest, and the development of an overhanging front. Thus, waves advancing over a bottom slope of 1 in 100 at St. Augustine, Fla., have been described as breaking where the depth was equal to their own heights in calm weather, at a depth 1.25 times as great as their own heights when the wind was strong onshore, but not until the depth was only 0.72 as great as their height when the wind was strong offshore (Gaillard, 1904, p. 120). In another case, near Bournemouth, England, a swell, causing a heavy surf, did not break until almost in on the beach after an offshore wind had risen, although the height of the breakers was about the same as it had been while the wind had been blowing onshore (Cornish, 1910, p. 88). The difference in this respect between onshore and offshore winds is often great enough to be worth taking account of in landing operations, even before the sea or swell shows any appreciable diminution in its height offshore.

The interaction, in short, is so complex between the factors involved that the nearest approach to a definite rule that we dare offer for the relationship between heights of breakers and depth of water, is as follows: If the bottom slope is gentle (less, say, than 1 in 40), waves may break where the depth is twice as great as their own heights if the wind is strong onshore, or if a strong current is running against them; they will be likely to break where the depth is about 1.3 times their own heights if the weather is moderate to calm, with little or no current; but they may not do so until the depth is only about three-fourths as great as their heights, if there is a strong offshore wind. If the slope of the bottom is steep or if it changes slope abruptly, it is safer to reckon on waves breaking where the depth is twice as great as their own heights, especially if the wind is blowing strong onshore or if there is a strong current against the waves, for while it is uncertain if the slope of the bottom, *per se*, has any effect on the depth at which the rollers break, it is always wise to be on the safe side when dealing with surf. Waves may even break where the depth is as much as three to six times their heights in extreme cases (p. 126).

It must be remembered that it is not the height that a wave may have had while out in deep water that is critical in this connection, but the height to which it may rise during its advance into shoaling water, which depends largely on its initial steepness, as explained on page 121. For example, a wave that was 2 feet high in deep water might be expected to break when it reached the 2.8-foot line, if its initial

length were only about 40 feet (ratio of 20:1), at the 3.6-foot line, if its initial length were about 200 feet, and at the 5.3-foot line if its initial length were about 500 feet, assuming that the condition of the wind and the slope of the bottom were such that the relationship holds. Allowance must therefore be made for the shapes of the waves offshore; longer waves will break at greater depths than will shorter ones, if of equal heights originally. If this factor is taken into account, and if it is assumed that the ratio between depth of water and height of breaker falls between about 1.3 to 1, and 2 to 1, as it usually does under ordinary conditions of wind and weather, waves of different heights initially, but of different degrees of steepness, may be expected to break at approximately the depths given in table 32.

We must call attention here to the fact that the ratio of length to height for breakers at the instant of breaking, as deduced from the theoretical relationship illustrated in figure 21 for waves advancing over an evenly shoaling bottom, is uniformly greater than the supposedly critical 7/1 (or than the inverse ratio of 0.14) unless they are as steep as that initially. And this discrepancy increases, the greater the original length of the wave is relative to its height, before it begins to feel the bottom in its advance shoreward. Thus, a wave 10 feet high originally should, theoretically, be about 7.4 times as long as high when it broke if it were 82 feet long (period 4 seconds) originally, about 10.6 times as long as high if its original length were 184 feet (period 8 seconds), about 14 times as long as high at breaking if its original length were 328 feet (period 12 seconds), and 24 times as long as high if it were 738 feet long initially (period 12 seconds). And we believe, from our own observations, that breakers commonly are considerably more than 7 times as long from crest to crest as they are high, although the very event of breaking makes it obvious that their crests have steepened to the point of instability.

The reason that waves do not reach the supposedly critical 7/1 ratio before they break is that the decrease in the length of a wave, that accompanies its advance over a shoaling bottom, involves an alteration of another sort in its profile, as has long been known, by which the troughs become so much longer and flatter but the crests so much shorter, that breakers caused by an old swell often appear as abrupt ridges separated by stretches of nearly level water. The result of this alteration is that the crests, acting independently of each other, steepen to the angle of instability while the lengths, from crest to crest, are still many times more than 7 times as great as the heights of the latter. It is only when the surf is the product of storm seas, steep enough to be breaking already, that this general rule does not apply in greater or less degree.

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THE STAGE OF THE TIDE AS IT AFFECTS THE SURF

It is common knowledge that the surf is much more violent at high tide than at low in regions where the coast is fronted by off-lying ledges that are bare at low tide but submerged at high, and where the rise and fall of the tide is great. The reason is obvious: the ledges act as natural breakwaters at low tide under these conditions, but not at high tide. The many ledges lying off the Cohasset shore in the southern side of Boston Bay (with which we ourselves have a lifetime familiarity) act efficiently in this way, when partly awash and partly bare, even though the wind may be blowing so strong onshore that a heavy sea is running outside. But the 9- to 11-foot rise of tide submerges them so deeply at high water that storm waves run right in across them, to beat directly upon the shore line. Situations of this sort are common along other rocky shore lines, including coral reefs.

The stage of the tide may affect the character of the waves in this same way over offshore bars because many of these rise so near to the surface of the water that a surf develops there at low tide, even though it may not at high. In such cases it may be possible to land at low tide on the beach behind the bar, if the latter is long enough and if one can come in around it, though the surf on the shore may be too heavy for this at high tide. The subject of bars is discussed further on p. 133.

An impression is widespread that the surf is also likely to be more violent and the spray to fly higher at high tide than at low along steep beaches in general, even if they are not protected by off-lying ledges or by bars. This impression may partly be due to one's natural tendency to class the breakers as higher if they form closer in to the beach, as at high tide, than if this happens farther out as at low, even though the actual heights of breakers may be the same in the one case as in the other. But there is in fact a considerable difference in the character of the breakers at high tide and at low (at least for regions where the rise and fall of the tide is considerable) along beaches that slope more steeply, as many do, above low-water mark than below it, because the alteration in the shape of the wave is distributed over a considerably greater distance (i. e., the rollers steepen more gradually as they near the breaker line) at low tide than at high. The increase in steepness, for example, of a wave that was 100 feet long in deep water would, theoretically, be spread over a distance of about 1,200 feet at low tide if the bottom sloped up evenly to the tide line at an angle of 100 to 1. If, however, the beach then steepened to 20 to 1, a common condition, the result of a rise of 10 feet in the water level would be to condense most of the alteration of the wave into the last

640 feet of its run, so that it would steepen nearly twice as abruptly, although its height might be the same when it broke in the one case as in the other. Breakers which steepen abruptly may be more difficult to cope with than ones that do so more gradually, so that the resultant surf is classed as "worse."

It will be convenient to discuss further effects of tide in the next section.

DISTANCE OF THE FIRST LINE OF BREAKERS OUT FROM THE SHORE; EFFECTS OF BARS; NUMBER OF LINES OF BREAKERS

It is not possible to lay down any one general rule for the distance out from the shore to the first line of breakers, for while this depends

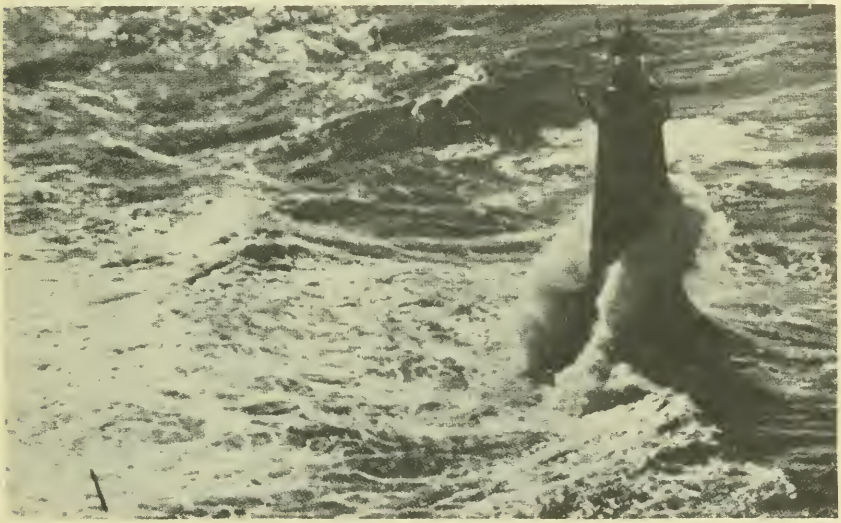

FIGURE 33.—A breaker in the process of development against the base of Minot's Light, Massachusetts, near high water on a stormy day. (Photograph, courtesy of Press Association, Inc.)

chiefly on the heights and lengths of the waves out in deep water and on the angle of slope of the bottom, other factors such as the evenness of the bottom, the direction of the wind, and currents (if any) all enter into the picture. The only general statement that can be made is that the distance of the breakers is that at which the water becomes shallow enough to cause the existing waves to break. At the one extreme there may be no surf at all (p. 102), or the waves may not break until they actually reach the foot of some lighthouse standing on a submerged ledge (fig. 33), or against cliffs and breakwaters (fig. 28). And the first heavy fall of broken water on a steep beach (fig. 34) or rocky shore line may be (and often is) right at the tide line. At the

FIGURE 34.—A wave about 6 feet high breaking close in to the tide line on a steeply sloping beach along the outer coast of Cape Cod. (Woods Hole Oceanographic Institution photograph.)

other extreme, broken water may extend out 2 to 3 miles, or even farther, if high waves are breaking in 3 to 4 fathoms or deeper on a gentle slope with a strong onshore wind, i. e., so far out that an observer standing on the beach near water level cannot see out past the limits of the zone of breakers (fig. 35).

The effects of offshore bars are very important in this connection, because these are developed by the actions of waves and tides, off many river mouths, off the mouths of shoal harbors, and even off straight beaches. It depends partly on the depth of the water over the bar whether surf will break over it at any given time, which in turn depends largely on the stage of the tide, but it also depends on the sizes and shapes of the waves; likewise, on tidal currents, because breakers develop in considerably deeper water if the tide is against the waves, than if the reverse is true, as explained on p. 55. And tides often run strong across bars and around them, especially off the mouths of large rivers, where the velocity of the ebb out across a bar is often so great as to cause a dangerous rip, when waves of any size are heaving against it from seaward.

Bars fall into two groups, as they bear on the surf problem: (*a*) those that lie off beaches, and (*b*) those that front the mouths of rivers or harbors. In the first instance the waves may break out along the bar, with little or no surf on the beach behind it (fig. 36, above). And this often happens if the weather is calm, and the sea smooth. Or they may break heavily on the beach, if they carry on across the bar without breaking upon it, or if the development of breakers on the bar does not destroy the wave forms there (fig. 36, below).

The presence of a bar across a harbor mouth may not hinder access to the latter so long as the waves are not breaking upon it. If they are, however, such a bar may prove an impassable barrier, and many "bar" harbors and river mouths are made inaccessible to shipping by stormy weather for considerable periods of time.

A heavy surf is also common well offshore, over submerged ledges and reefs off rocky coasts. And the waves may be expected to break in considerably deeper water there than on the beach, because of the abrupt alteration in the angle of slope of the bottom that characterizes such situations. Old swells, not over 1½ to 2½ feet high offshore, that we recently observed breaking in a depth of 5 to 6 feet, over a ledge in the southern side of Massachusetts Bay, may serve as an illustration.

The behavior of waves, as they advance across bars or ledges, has not received as much attention as it deserves, perhaps because close observation on the spot is difficult, or even risky. In any event, great caution is always advisable, when coming in across a bar, or especially

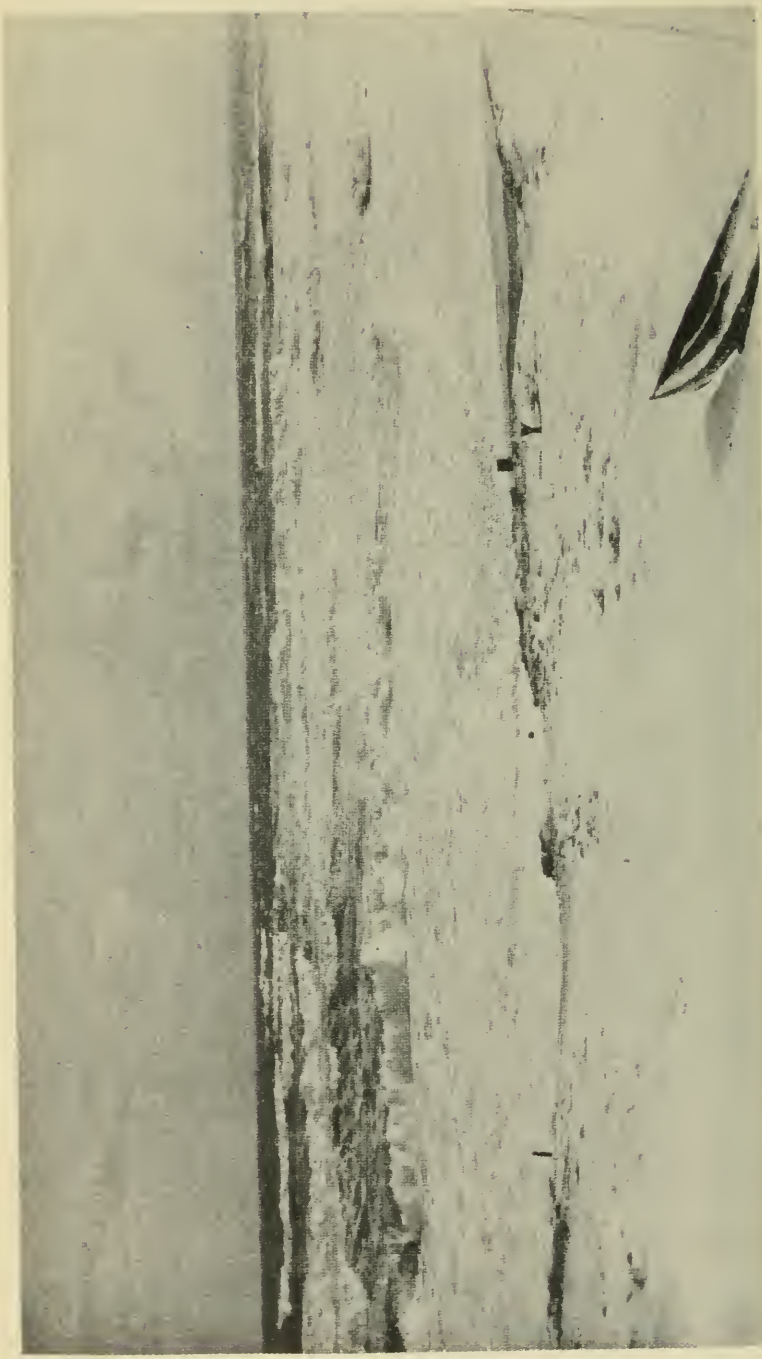

FIGURE 35.—Surf caused by rough seas extending out about 5,000 feet from shore off Pinm Island, Massachusetts. (U. S. Coast Guard photograph.)

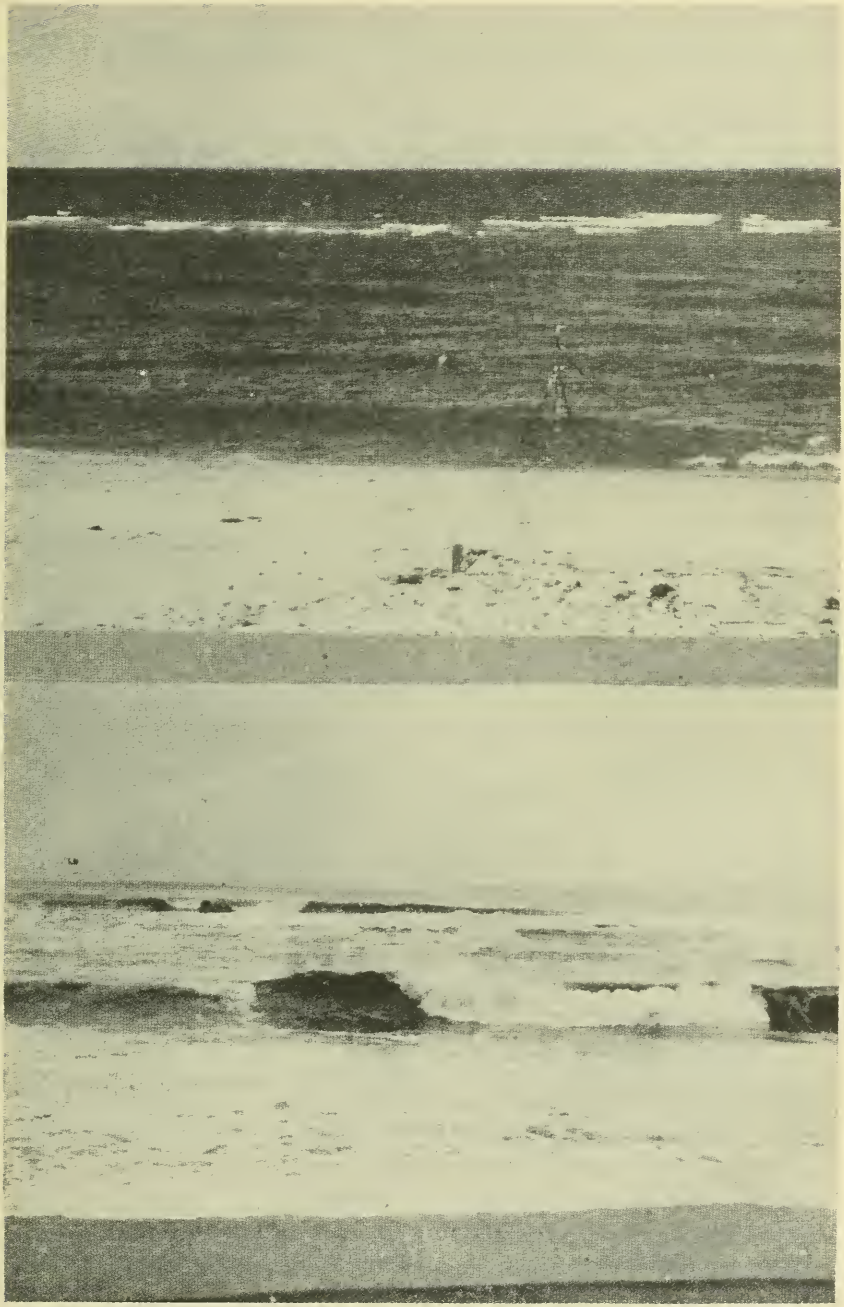

FIGURE 36.—Surf developing over bars along the outer coast of Cape Cod, with little or no surf on the beach (above) and with moderately heavy surf on the beach as well as on the bar (below). (Woods Hole Oceanographic Institution photographs.)

across a submerged reef, even if the passage seems to be safe as viewed from the seaward, especially if a swell is running, because an occasional wave may rise so high that it falls forward in an acre or two of swirling foam and broken water, even at times when the common run of waves cross without breaking. We have time and again seen this happen.

The number of lines of breakers varies as widely as does their distance out from the coast. If the first heavy fall of water is right on the shore line, there may be only one line of true breakers, besides the zone

FIGURE 37.—A typical surf, with two chief lines of breakers, off a rocky coast of the Hawaiian Islands in moderate weather. (Photograph, courtesy of W. J. Clench.)

of foaming water that surges up and down the beach (fig. 34). If, however, the first line of surf is far offshore, there may be 2 (figs. 24, 26, 37) or even as many as 5 or 6 lines of breakers, or even more (fig. 38, 39), the outermost of which is usually the most dangerous.

The governing factors here are chiefly the degree to which successive waves differ in shape and in dimensions, one from the next, while they are still out in deep water; and the contour of the bottom, whether sloping gently or steeply, uniformly or in successive steps—the presence of an offshore bar represents an extreme case. The more widely the successive waves differ one from the next in height and in length, the more numerous will the lines of breakers be, because the higher and longer waves will break in deeper water, hence farther out from the land, than the lower and shorter ones. And there may be several lines of breakers, even with very regular swells, for each of them may still

retain their identity after they first break sufficiently for them to crest and break again, and perhaps again, as they come into shoaler and shoaler water. It also happens commonly that a breaker of the spilling

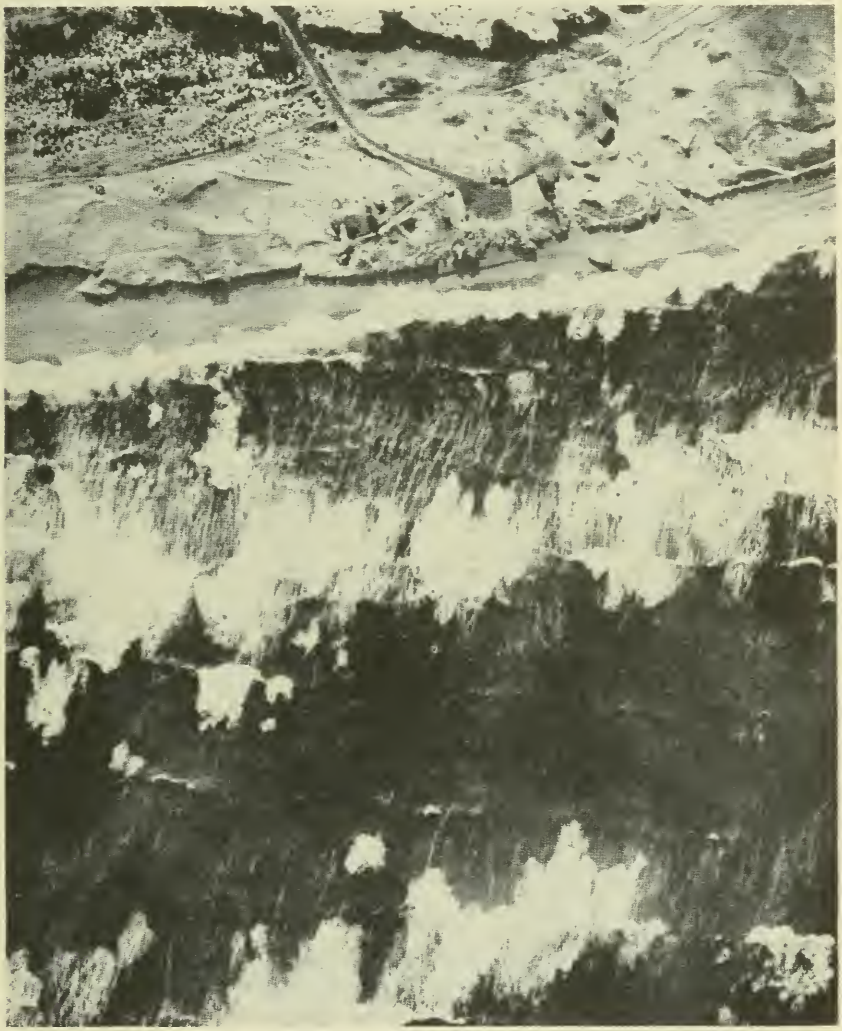

FIGURE 38.—Aerial photograph showing moderately heavy breakers on two bars, as well as on the beach behind them, near Race Point, Cape Cod, November 18, 1944. (Photograph by Photo Squadron 2, Norfolk Naval Air Station.)

type (p. 111) is still travelling toward the land when the next wave breaks behind it, and perhaps a third and a fourth if conditions are right. The matter is still further complicated by the fact that while one wave may break abruptly, the next may do so continuously as it

advances shoreward, as described on page 115, while still a third may do so intermittently, so that it alone may be responsible for several lines of breakers, before it is extinguished finally on the beach.

The sidewise extent of the individual crests also enters into the situation, for when this is wide (as it is for swells), the breakers will extend correspondingly far sidewise, and the number of lines of surf will be more constant than when the crests are narrow laterally, as they are if the waves are younger. In the latter case, patches of surf may alternate irregularly with lanes or patches of unbroken water, so that the number of lines of breakers is changing constantly. The breakers caused by storm seas therefore vary widely in size, one from the next; they are also very irregular in their surface contours. And they break at different times along different fronts. Added to this, storm seas that are already breaking offshore may continue to do so with increasing violence, as they advance into shoaling water, causing a confused zone of heavy surf perhaps hundreds of yards wide, so varied in pattern and so constantly changing that no definite number of lines of breakers can be counted, even along a narrow front. Indeed, there may be no sharp line of transition, during an onshore storm, between the breaking of the seas offshore, that is caused by the wind alone, and the surf zone that develops because of the shoaling bottom.

The lines of breakers that are caused by a swell are much more regular, not only in number and in their distances out from the land, but also in the sidewise extent of each crest, while the outermost line of surf breaks fairly regularly along a comparatively narrow depth zone of the bottom. Further, the waves usually are not breaking at all to seaward of the outermost line of surf. Under these circumstances, the crests often extend far sidewise—perhaps as much as 1,500 yards.

The angle at which the bottom slopes also plays a very important part in determining how many lines of breakers there will be. The one extreme in this respect is exemplified by a steep headland or breakwater, or a very steep beach, against which the surf may break in a single line as described above (p. 138), irrespective of the initial shapes of the waves. Gently sloping foreshores exemplify the other extreme, where there may be many lines of breakers (fig. 35), for succeeding waves will break before preceding ones have reached the shore. And the situation may differ widely in this respect on a given beach, at different stages of the tide, for the slope is much more gentle below low-water mark than it is between low-water mark and high-water mark in many localities. Under these conditions there may be anywhere from only one or two lines of breakers to as many as five or

FIGURE 39.—Five or six lines of breakers, the outermost being much the highest, on a gently sloping beach at low tide, with an onshore wind strong enough to cause the waves to break well offshore as well. (U. S. Coast Guard photograph.)

six, or even more (fig. 39), at different stages of the tide. In localities where shoal spits or bars extend out from the tide line, alternating with deeper gullies, the surf belt is likely to be interrupted over the latter by lanes of unbroken water, extending close into the strand. And the presence of a lane of this sort, between patches of surf, usually indicates a gully, if it persists in the same location, for while similar lanes are to be seen wherever the wave crests are narrow sidewise, they are short-lived in that case, developing now here, now there. The effects of bars and gullies of this sort, like that of the angle of slope of the bottom in general, is often dependent on the stage of the tide, as illustrated by the differences in the surf pictured in figure 40 which was photographed from the same view point, but at high water in the one case, at low water in the other.

The types of surf that result from the interaction between bottom contours, shapes and sizes of waves, and stage of the tide may be classed roughly as follows:

a. A single line of breakers with their crests dashing directly against the shore line (figs. 28 and 34). This type is characteristic of the surf that develops against steep ledges and against breakwaters that rise from a depth of a fathom or more, or on any steeply sloping beach when the waves are small.

b. Breakers close in to the shore, with a belt of foaming water between them and the beach (fig. 27). This type is encountered most often along steeply sloping beaches when the tide is high or nearly so.

c. A single nearly continuous line, with lower breakers inshore from it. This condition is commonest in moderate weather where swells are running in over an even and gently sloping bottom.

d. Two, three, or more nearly continuous lines of breakers, the outermost of which is usually the highest but sometimes with all of approximately the same heights (fig. 39). Like the last, this type occurs most frequently in moderate weather when swells are moving in over a gently sloping bottom.

e. Several lines, covering the surf area as a whole, and varying in number not only from moment to moment, but from place to place as well. Such a surf is often observed during onshore winds of moderate strength.

f. Confused breakers in indefinite lines from seaward, grading into a breaking sea offshore (fig. 35). This pattern is characteristic of onshore storms, whether on beaches or against rocky coasts (fig. 41).

FIGURE 40.—Low breakers over two neighboring shoals on the outer coast of Cape Cod, interrupted at high tide by a lane of unbroken water extending shoreward to the beach (above) and the same locality at low tide (below). (U. S. Coast Guard photograph.)

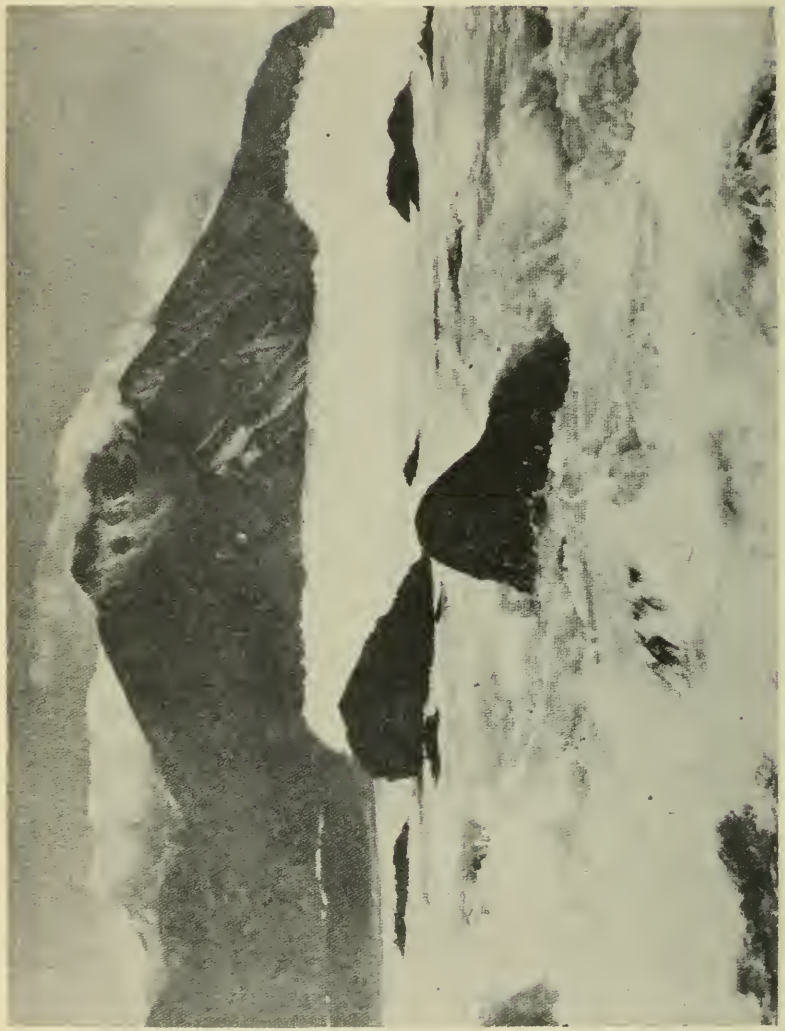

FIGURE 41.—Very heavy breakers over the rocks off Adak in the Aleutians. (Official U. S. Navy photograph.)

FACTORS THAT HINDER THE DEVELOPMENT OF SURF OR THAT TEND TO INTERRUPT IT

Ledges, shoals, and islands.—The types of surf just described are those that develop where the bottom is comparatively smooth, as it usually is off sandy beaches and off rocky coasts in many parts of the world. But the development of breakers may be interrupted more or less, in regions where the bottom is strewn with large boulders, or is interspersed by submerged reefs. The latter, if rising near enough to the surface for the waves to break over them are especially effective in this respect, as described on page 132. And small islands scattered within a bay, or at its mouth, provide still better protection. Thus the surf breaks heavily at the mouth of Casco Bay on the coast of Maine, during southerly and southeasterly storms (also during calms if a swell is running), but the islands farther in protect the inner parts of the bay to such an extent that its head is free from surf of any size, at all times. And many other examples of this same sort might be cited.

The effects of bars near the coast have been discussed already (p. 132). Deeper and more extensive shoals farther offshore, such as the great fishing banks of the North Atlantic, may also interfere with the advance of ocean waves to some small extent. The effect of Georges Bank, for example, crowned by the much shallower Georges Shoal, with the tidal currents that run around and across it, so hinders really long swells from the open ocean that these seldom reach the western shores of the Gulf of Maine, though the distance from the bank in to the shore is enough for a heavy surf to develop there during onshore gales, or when storms pass by to seaward. And Nantucket Shoals, which is shallower than Georges Bank, protects Martha's Vineyard island rather more effectively from storm waves coming from eastward, though leaving it open to waves from the southward and southwestward.

Tidal currents.—Oncoming waves that meet a contrary current, while they are still some distance out from the land, or one transverse to their own line of advance, may either be caused to break far out, or be deformed in some other way, so that the shore line where they would otherwise develop into breakers may be protected, more or less, from surf, at least until the tide changes.

For example, waves from offshore are so combatted by the swift and confused tidal currents at the mouth of the Bay of Fundy, which is some 30 miles across and wide open to seas from anywhere between southwest and southeast, that surf developing up the bay is largely of local origin. And the protection from the waves of southwest storms that the southern coasts of the Shetland Islands receive in this

same way by tidal currents, during the periods when these are running strong along the coast, is proverbial; the surf breaks on the shores there with great force during stormy weather, as soon as the current slackens (Stevenson, 1874, pp. 61–62).

Rip currents.—The water that is carried landward by the surf is returned seaward, in many localities, by local currents flowing offshore, or "rip currents," a name which must not be confused with "tide rips" because they have nothing to do with the tide. They have been studied along the coast of California chiefly,[41] but they are to be expected along any open coast where heavy waves break commonly. They are

FIGURE 42.—Aerial photograph showing a rip current off Coronado Beach, California. (Official U. S. Navy photograph.)

not known to extend more than half a mile or so out from the beach, and they are usually less than 100 feet across at their inshore ends, but they widen more or less at their offshore ends. (fig. 42). They are temporary phenomena only accompanying high breakers and dying out when the surf flattens, but their velocities may be considerable in their narrow inshore necks. One, for example, that was recently observed on the outer coast of Cape Cod was flowing at an estimated velocity of at least 1.5 knots. Waves running in against a rip current are steepened as they are by any contrary current of equal velocity, so that they may break much farther out than would otherwise happen, and in a very choppy and irregular fashion, much as in any ordinary tide rip (fig. 32). A current of this sort may thus cause a more or less definite gap in the lines of surf, if the latter is a regular

[41] For an excellent account of rip currents, see Shepard, F. P., K. O. Emery, and E. C. LaFond, 1941, Rip currents; a process of geological importance. J. geol., vol. 49, pp. 337–369.

one caused by swells. On the other hand, a rip current may accentuate the irregular and tumultous nature of the surf if this is due to storm seas.

Hail and ice.—It is common knowledge that a hail storm tends to knock down a sea, and hence to reduce the surf, even though the wind may be high. And loose pack ice, so kills a sea that a vessel following the lanes through it may be sailing in smooth water (fig. 43), even when a gale is blowing and the waves are breaking heavily against the exposed edges of the pack. During the days of sail, many a whaler found a safe natural harbor from storms in this way. When ice crystals form in the water, they smooth the waves much more efficiently than a film of oil would, so greatly does their presence increase the internal friction among the water particles even before they become solidified. We have, for example, seen at Barnstable Beach, Massachusetts, a moderately heavy sea (wave height estimated at 4 to 8 feet) that was breaking offshore, under a winter gale, so smoothed out in its passage through the last 100 feet or so of water soupy with ice crystals, that it simply rose and fell against the 5- or 6-foot ice barrier without breaking at all. Snow falling on the water has a similar mechanical effect, though in a lesser degree.

Marsh grasses and seaweeds.—A tall growth of marsh grasses may so obstruct the waves in an estuarine situation and on a marshy foreshore, during the stage of the tide when it is partially submerged, that a belt a few yards wide may wholly prevent breaker formation, even in weather when there is considerable surf on neighboring stretches of beach that are not protected in this way. We think in particular of a certain gently sloping beach between rocky headlands on the south shore of Boston Bay, where we have often landed our dory with ease through a patch of partly submerged marsh grass (*Spartina*), an acre or less in extent, at times when the surf would have made it difficult for us to have done so on the bare beach close by.

A thick growth of seaweed, the fronds of which are long enough to reach to the surface, may afford considerable protection to an exposed anchorage, as is said to be the case at Kingston, an open roadstead in Lacepede Bay, South Australia, where ships loading with wheat can lie safely during northwest storms, though a heavy surf develops along the neighboring coast.[42] Similar conditions no doubt exist on a small scale elsewhere.

Darwin long ago stated that beds of giant kelp (*Macrocystis*), which may reach to the surface from depths as great as 45 fathoms, make excellent natural breakwaters in the Straits of Magellan, remarking that waves from the sea soon decrease in height and are

[42] Interesting accounts by ship captains are to be found in Nichelson, J. G. 1888. Aus dem reisebericht der . . . "Franz." Ann. hydrogr., Berlin. vol. 16, p. 22.

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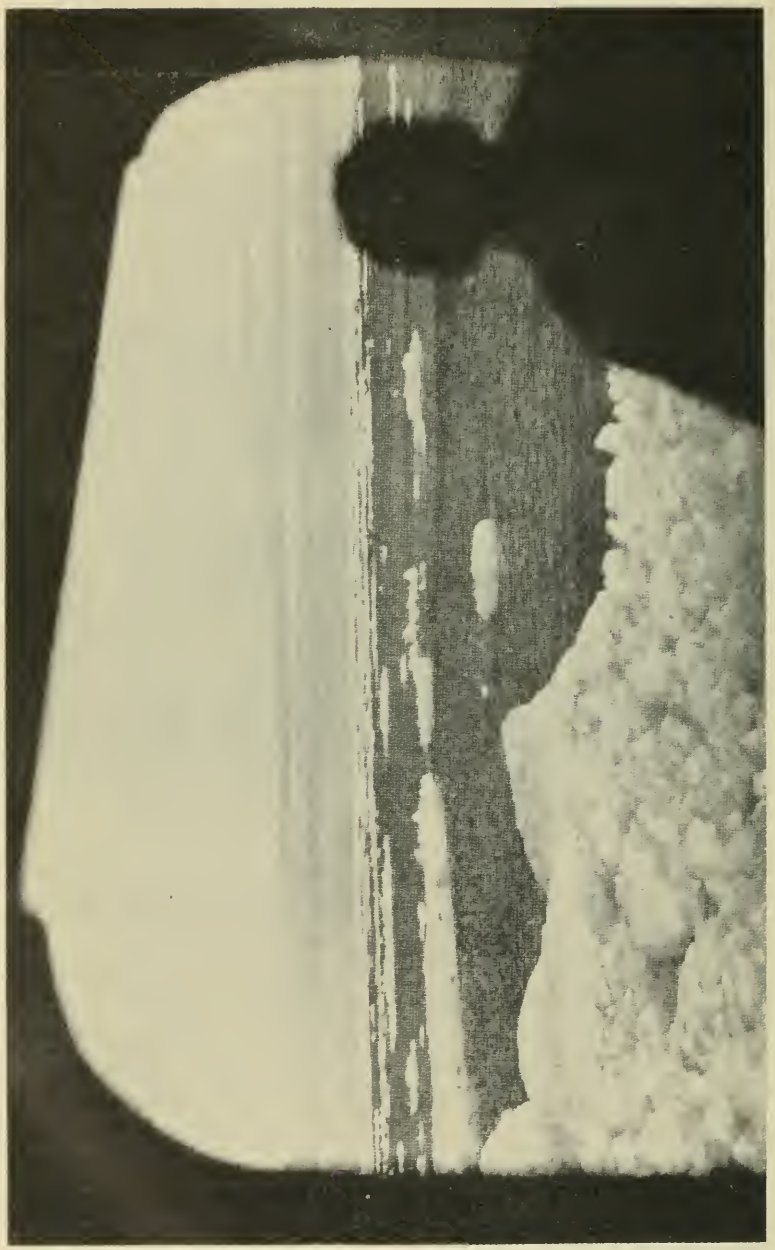

FIGURE 43.—The smooth sea in an ice field, as viewed from a U. S. Coast Guard Cutter. (Official U. S. Coast Guard photograph.)

smoothed out in their advance through the weed.[43] Waves, however, that advance through narrow beds of giant kelp that are separated from the shore by zones of open water, as is the case at many points along the Pacific coast of the United States, may still cause a surf, the severity of which depends partly on the breadth and density of the floating barrier in question, but partly on the original shapes and dimensions of the waves, because storm seas are dampened down to a greater degree than swells are, in their passage through the kelp.

Dense beds of the so-called "eelgrass"[44] combatted the development of breakers in much this same way, in many shallow estuarine situations, during stages of the tide when its leaves floated up to the top of the water, until a parasite almost exterminated this common plant far and wide, not only along the northeast coast of North America, but along the northwest coasts of Europe as well. The rock weeds (*Fucus*, *Ascophyllum*) may act similarly, though on a very small scale, around the more protected sides of some offlying ledge at low tide, when floating fronds may tend to dampen down the waves. It may then be possible for collectors of seaweed to work there, or for crabbers or anglers to land, until the tide rises, when the fronds of the rock weed become submerged so deeply that they no longer afford any protection.

Patches of floating "gulfweed" (*Sargassum*) in the so-called "Sargasso Sea" have a similar effect on local waves, as we have often observed. But gulfweed does not occur coastwise in sufficient quantities, nor are the drifting beds of it stationary enough, to be of any importance in the surf problem.

Oil.—The calming effect on waves of a film of oil has been known for ages; Pliny, for example, mentioned it in the year 77 A. D. And every work on seamanship includes directions for its use in storms. Briefly, oil extinguishes the smaller wavelets, and—its especial value—prevents the waves from breaking. It is not clear just how this is brought about, for the older view that its effects are due to lessened friction with air seems not to be correct, while it is doubtful whether more recent explanations, based on the relative viscosity and surface tension of oil as compared with water, are adequate. But in any case, a film of oil spreading over storm seas, so lessens the grip of the wind on them, that it immediately causes them to assume the character of swells, and thus renders them much less dangerous. Oil, however, does not interfere appreciably with the development of surf, for in this case it is not the immediate effect of the wind that is responsible for the formation of breakers. But oil may be of real assistance if it is

[43] Darwin, Charles. 1871. Journal of researches into the natural history and geology of the countries visited during the voyage of H. M. S. *Beagle* round the world. N. Y., p. 240.

[44] Eelgrass (*Zostera*) is a flowering plant in reality, not a true "seaweed" or alga.

necessary to attempt landing during onshore winds strong enough to cause a breaking sea offshore, for its use may prevent the waves from breaking until they reach the surf line, proper.

THE PERSISTENCE OF SURF AND ITS RELATIONSHIP TO THE WIND

The regularity of the breakers, locally or seasonally, and the length of time during which a dangerous surf may persist, depends on the regularity of the wind, either nearby, or in storm centers at a distance. The Trades are the most regular winds of the world; consequently the surf is the most nearly regular in the downwind parts of the Trade Wind Belts of the Atlantic and Pacific, north and south, and of the Indian Ocean south of the equator. Classic examples are the breakers on the windward shores of the Lesser Antilles, and the surf of the island groups and atolls of the western tropical Pacific facing the sweep of the Northeast or of the Southeast Trades, at the time of year when these are the most regular in direction and blowing at their highest average velocities. Surf also runs on the east coasts of Madagascar, of Mauritius, and of Reunion, more or less the year round, and on the Seychelles from June to October, for this same reason. A heavy surf is to be expected, nearly or quite as regularly, along the coasts of the Arabian Sea, northward from the vicinity of Bombay, right around to Arabia, during the season of the Southwest Monsoon, June to August.

The windward shores of the northern atolls of the Maldive group and of the Laccadives are also the sites of constant surf at this same season, though it is not often as heavy there as on the island groups of the central and western Pacific, to judge from the fact, to which we can bear witness, that the coral boulders thrown upon the Maldive reef flats are "mere pigmies compared to the gigantic masses moved on some of the reef flats of the Pacific reefs." [45] And breakers dashing against the breakwater of Colombo Harbor, Ceylon, through the Southwest Monsoon have been the subjects of many spectacular photographs.

Exposed coasts in the West Wind Belt of the Southern Hemisphere—the "Roaring Forties" of sailing ship days—and the corresponding coasts on the eastern sides of the North Atlantic and of the North Pacific are also battered by breakers of dangerous height, day after day, during the stormy season. Familiar examples are the winter surf on the coasts of northern California, Oregon, and Washington, in the Pacific; of western Ireland, Scotland, and the Faroes in

[45] Agassiz, Alexander. 1902. An expedition to the Maldives. Amer. j. sci., ser. 4, vol. 13, p. 307.

the Atlantic. And every sailor has heard of the surf around southern Staten Island and Cape Horn.

Surf, however, is never a wholly regular phenomenon anywhere. Even the Trade Winds do not blow with perfect regularity, but are stronger, on the whole, by day than by night, and at one season of the year than at another. They are also punctuated from time to time with gales of greater or lesser severity on the one hand, and by light breezes, on the other, while they are deformed wherever they blow over or around land masses of any size. They may also be interrupted more or less, near the coast, by the development of a land breeze at night. And the surf caused by the Trades varies correspondingly, though it may never cease wholly on the exposed shore of a coral atoll during the Trade Wind season.

Regions where the breakers on the coast are the products of passing storms, rather than of prevailingly onshore winds, or where they are caused by swells that radiate out from storms passing at a distance, illustrate the opposite extreme. Under these conditions the surf may vary very widely in violence from place to place, from day to day, and even from hour to hour. The beaches of the middle Atlantic coast of the United States, where the prevailing winds are offshore, or along the shore, and where sea breezes are usually light, afford an excellent example, for it is only during onshore storms that a high surf develops there, or during the rather rare occasions when a heavy swell is heaving in. This may be illustrated by the rarity of breakers higher than 10 feet (or even higher than 5 feet) that are recorded at Coast Guard stations, on the beaches of Long Island, New York, New Jersey, and the northern part of North Carolina (table 34). In fact, it is possible to launch a boat from the beaches of our middle Atlantic States and bring it in again on three days, perhaps out of four during the summer, and on one day out of three or four even in the winter, something that would not be possible at all, on any exposed coast in the downwind parts of the Trade Wild Belts, during the windy season.

TABLE 34.—*Number of days when the average heights of the highest breakers were greater than 5 feet and greater than 10 feet from January through April 1945, at different localities along the east coast of the United States*

[From data obtained through the cooperation of the U. S. Coast Guard with the Woods Hole Oceanographic Institution]

Locality	Number of days	
	Over 5 feet	Over 10 feet
Plum Island Coast Guard Station, Mass.	15	2
Highland Coast Guard Station, Cape Cod, Mass.	29	6
Georgica Coast Guard Station, Easthampton, Long Island, N. Y.	34	1
Ship Bottom Coast Guard Station, N. J.	12	0
Kill Devil Hill Coast Guard Station, N. C.	6	0

FIGURE 44.—A breaker, on the coast of New Jersey, developing from an old swell against an offshore wind strong enough to blow the spray backward from the crest as the latter plunges forward. (Woods Hole Oceanographic Institution photograph.)

The surf is much more persistent, and much more regular in its characteristics, along the western coast of the United States than along the eastern, because the prevailing winds are more often onshore there, and so tend to build up the waves (seas or swells) that come in from the seaward, or at least do not tend to beat them down. The surf that is raised daily through the summer, near Monterey, Calif., by the brisk sea breeze that springs up with astonishing regularity each morning at that season, to die down again at sunset or soon after, affords a good illustration of this regularity.

Surf caused by waves that are generated nearby dies so soon after the wind falls, or when the latter shifts in direction (because of the decrease that takes place then in the sizes of the waves offshore), that the breakers due to storm seas may decrease to manageable proportions within a few hours. But a dying wind or even a calm, near the beach, may not decrease the surf at all if the breakers are caused by swells coming from a distance. This phenomenon is of much practical importance, for anyone not instructed in the matter might naturally expect to find landing easy in calm weather, whereas the surf from a swell may actually persist for a considerable period of time even in a flat calm, as described above (p. 99). We ourselves observed a very regular and persistent swell on one occasion, on the west coast of Ceylon, throughout the 36 hours of our stay, although there was hardly a breath of wind stirring. A light cross wind may also interfere very little with surf from an old swell, so long as the waves produced by the wind are not large enough to interfere seriously with the wave pattern of the swell, and a heavy surf may even persist against a strong offshore wind (fig. 44) until the latter has had time to kill the waves offshore, because the time occupied by each breaker in its development over the shoaling bottom is not long enough for the wind to combat it effectively before it reaches the breaker line.

Chapter 8

DIRECTION AND HEIGHT OF BREAKERS IN RELATION TO THE SHAPE OF THE COAST

It is much the easiest, and the safest, to bring a boat in end on, if the breakers are large enough to be troublesome, lest she be swamped. Hence, it may be important to know the angle at which the breakers are striking the shore.

THE REFRACTION OF WAVES

The angle at which breakers strike the shore is governed by the general direction of advance of the waves offshore in relation to the contour of the bottom and to the shape of the coast. Observers not accustomed to surf are often astonished to find that the breakers may be striking the beach at only a small angle, even at times when the line of advance of the waves of swells out at sea is parallel to the general trend of the coast. This is because the inshore ends of the waves are delayed in their advance by the shoaling bottom, as explained on pages 56 and 103, while their crests farther out are moving more rapidly; consequently their inshore ends are bent around or "refracted," as the alteration is commonly termed. It is often easy to observe this refraction, if one looks out over the water of some cove, pond, or river, when a smart breeze is blowing parallel to the shore, and it is shown clearly on photographs taken from airplanes (fig. 45).

The amount that a wave approaching the coast is refracted can be calculated, provided that the angle is known that it makes with the coast while it is still in deep water, that either its length, its period, or its velocity is known there, and that the shape of the bottom is also known. The relationship for straight beaches with parallel bottom contours is summarized in table 35.[46]

In general, short waves are refracted less than long ones, unless they advance into very shallow water indeed, because they are slowed less, as described on page 104. Old swells are thus bent around much more than younger storm waves are. Table 35 also illustrates another interesting point namely, that the surf often breaks on the beach much more obliquely than one might gather from a cursory reading of the literature on waves. A high wave, too, of a given length, suffers less

[46] The basic formula is: $\frac{\sin \alpha}{\sin \alpha_o} = \frac{C}{C_o}$; where α_o is the angle offshore, α is the angle at any given point inshore, and C_o and C are the corresponding velocities.

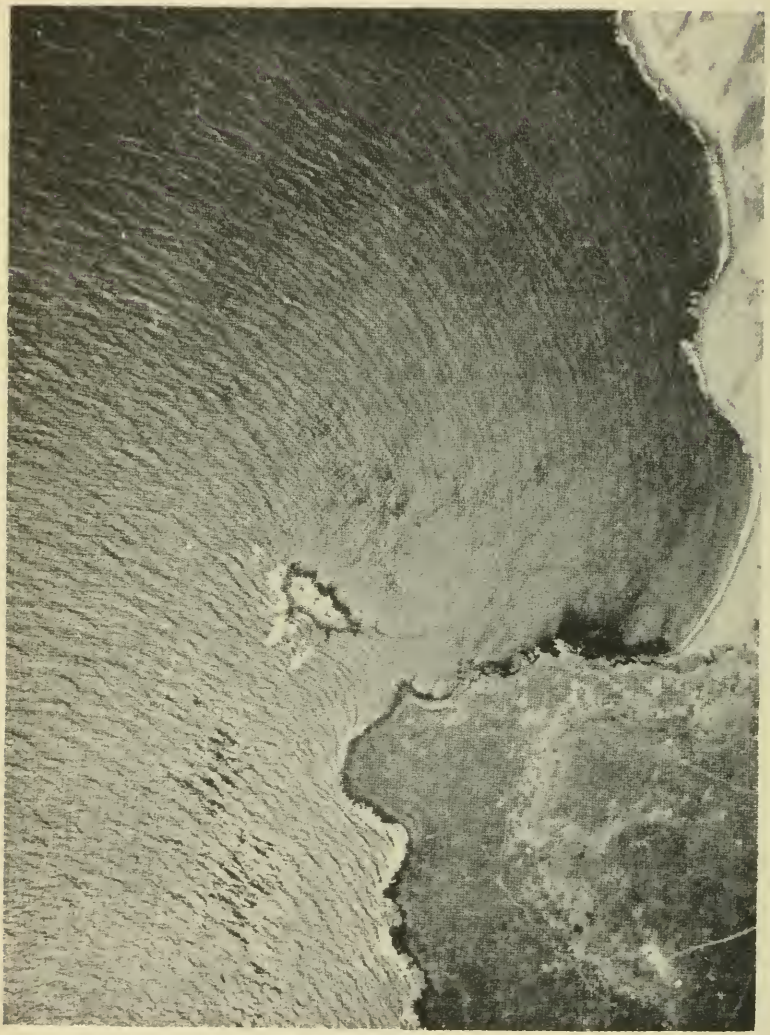

FIGURE 45.—Aerial photograph showing the refraction of waves around a headland and islet and into a bay at San Clemente Island, California. (Official U. S. Navy photograph.)

refraction before it breaks than a lower one of the same length, because it breaks in deeper water; hence, it may break at a considerably greater angle with the coast.

TABLE 35.—*The angles which breakers make with a straight shore line, when all bottom contours are parallel with the beach, for waves of different degrees of steepness in deep water approaching the shore line at different initial angles. It is assumed that the waves will break where the depth of water is 1.3 times the breaker height*

Steepness of wave in deep water (length: height)	Angle between wave in deep water and shore line						
	10°	20°	30°	40°	50°	60°	70°
10:1	9	16	23	30	36	41	46
20:1	6	10	15	20	23	27	30
40:1	5	9	13	17	20	23	25
100:1	3	7	10	12	15	16	17

The alteration in the angle between a wave and the coast that results from refraction is both gradual and cumulative, so that the crest becomes more and more strongly curved in toward the beach. Calculation of the precise shapes of such curves is complex, for it involves the determination of the velocity of the wave at different points along its crest at successive intervals of time, from which the successive positions of these points can be plotted. But the degree to which a wave is refracted over straight and parallel bottom contours can be pictured roughly by laying its crest down as a series of short chords crossing one contour of the bottom after another, at the angles indicated in table 36, as has been done in figure 46, for a wave, the offshore ends of which are at an angle of 70° with the coast line.

TABLE 36.—*The angles which waves (approaching at different initial angles) make with a straight shore line in diminishing depths of water (relative to the length of the wave in deep water)*

Depth of water in terms of wave length offshore	Initial angle of wave in deep water with shore line							
	10°	20°	30°	40°	50°	60°	70°	80°
0.500	10°	20°	30°	40°	49°	59°	68°	77°
0.400	10	20	30	39	49	59	68	77
0.300	9	19	29	38	47	56	64	71
0.200	8	17	26	33	42	50	57	61
0.150	8	16	24	31	39	44	50	53
0.100	7	14	21	27	32	37	41	43
0.050	5	10	15	20	23	27	30	31
0.030	4	9	12	16	18	21	24	25
0.025	4	8	11	14	17	20	22	23
0.020	3	7	10	13	15	17	18	20

THE LOSS OF WAVE HEIGHT BY REFRACTION

Refraction also affects the heights of waves, for when their inshore ends are delayed, while their offshore parts continue to advance unchecked, they are expanded sidewise—are stretched out as it were.

And the inshore ends tend to lost height in consequence, because the energy that the waves carry with them is spread through a longer distance by this alteration. Theoretically, this decrease in height is inversely proportional to the amount of sidewise expansion.[46] And since the amount by which a wave crest is expanded sidewise in this way depends on how much it has been refracted, it follows that the greater the angle is between the wave in deep water, and the coast, the more the wave tends to lose height as it is refracted around. Table 37

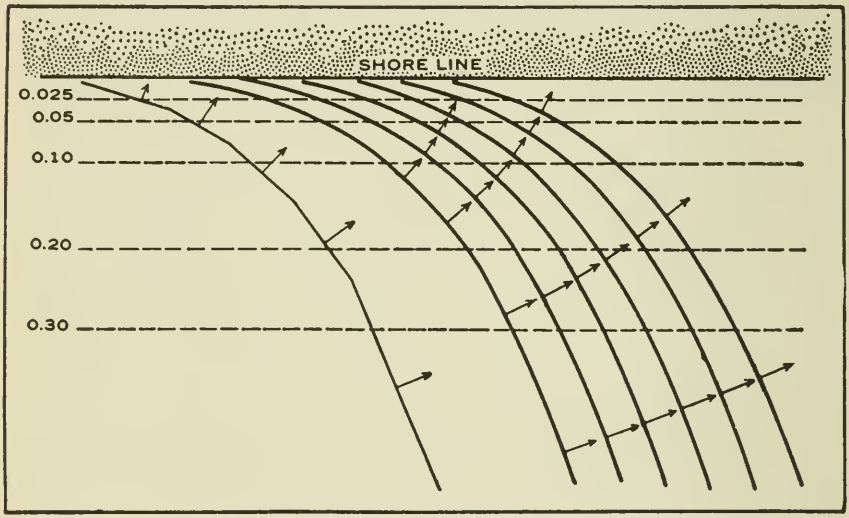

FIGURE 46.—Diagram to illustrate the refraction of waves along a straight shore line, when the wave crests in deep water form an angle of 70° with the coast. The depths of the bottom contours are given in terms of the offshore wave length. The wave crest at the left has been plotted by the simplified procedure described on page 157. The arrows indicate the lines of advance of the waves at successive points along their crests.

shows the theoretical loss in height by refraction for waves of different degrees of steepness, coming in at different angles.

Multiplication of the heights offshore by the ratio given in the appropriate column of table 33 (p. 121) will give the approximate height, at breaking, for waves of varying degrees of initial steepness, coming in parallel with the shore. And a further correction of the heights calculated in this way, using the percentages given in table 37 will

[46] According to the equation: $H = H_o\sqrt{\frac{dl}{dl_o}}$; where H_0 is the height of the wave over deep water; H, its height when it strikes the beach; dl_o, the sidewise extent of a given segment of its crest over deep water; and dl, the sidewise extent of this same segment of its crest at any given point during its advance shoreward. But the few pertinent observations indicate that waves which have been refracted through large angles are somewhat higher than indicated by this equation, suggesting a flow of energy sidewise along their crests. There is reason to believe that the effect of refraction is slightly different for waves of different steepness, but the matter has not been studied in detail.

give the approximate height of breaker, for waves that come in obliquely, provided always that the bottom is smooth, with a similar slope off all parts of the beach. Calculations of this sort are not as simple as they sound if precision is sought, because they involve an exact knowledge of the initial ratio between the heights of waves offshore and their lengths—or between their heights and their periods, which last can be translated into length. But it is not difficult to make rough estimates of heights and periods of waves, if the weather is moderate; and estimates of the height of the surf are not likely to be helpful, except in moderate weather.

TABLE 37.—*Percentage decrease in height between deep water and the breaker zone, for waves of different initial degrees of steepness approaching a straight shore line (with straight and parallel bottom contours) at different angles. It is assumed that the waves break where the depth of water is 1.3 times the breaker heights*

Steepness of wave in deep water (length:height)	Angle between wave in deep water and shore line					
	20°	30°	40°	50°	60°	70°
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
10:1	0	3	6	11	18	30
20:1	0	5	10	16	26	38
40:1	1	6	11	17	27	39
100:1	2	6	12	19	28	40

As a general rule, the decrease in the height of surf due to refraction is negligible for waves that come in at angles smaller than, say, 30°, no matter what their steepness may be offshore. But when the waves are coming in at an angle greater than, say, 60°, the decrease in their heights may make landing possible at a place where this would not be so otherwise.

Waves advancing in a uniform direction are refracted to the same degree all along a coast that is straight, if the bottom contours are parallel with the shore line (fig. 46); hence the decrease in their heights (if any) from this cause will be as great at one point along the shore as it is at another. But if the coast is strongly curved, the waves are refracted much more at one place than at another, so that the breakers may differ considerably, in their heights, from place to place. The local differences in the character of the surf that results are most conveniently discussed (*a*) around the shores of bays and beaches, and (*b*) around headlands and in the shelter of these.

SURF AROUND THE SHORES OF BAYS

Bays can be classified, roughly, as short and broad, or as long and narrow.

Wave crests that are parallel to the general trend of the shore line are not refracted at all along the central sector of a short, broad beach,

and the only change in their heights there, as they near the breaker line, is such as may be directly due to their advance over the shoaling bottom. But it is evident that the waves offshore might be at a considerable angle with the coast around the flanks of a beach of this shape; hence they would be refracted there to a degree depending on the precise shape of the coast, on the contour of the bottom, and on the initial shapes and dimensions of the waves, as explained above (p. 155).

Calculation of the precise amounts by which refraction affects the heights of waves at successive places around a curving coastline involves tedious computations. But the approximate amount of reduction, from refraction, to be expected from place to place, for waves of different degrees of steepness, may be taken directly from table 37, if one first marks on the chart the general trend of the wave crests offshore, and then measures the angle at different places between the latter and the depth line where surf is to be expected with waves of the heights that are running at the time. In the case, for example, that is represented above in figure 47, where the wave crests offshore are parallel with the central sector of the bay, but make an angle of about 40° with its flanks, refraction would tend to reduce their heights by about 10 to 12 percent at the points marked B and C by the time they broke, if they were 20 to 100 times as long as high while still out in deep water, and if they broke where the depth was equal to 1.3 times their own heights at that moment, but by only 6 percent if they were only 10 times as long as high to begin with. Reduction of the wave heights by refraction would naturally be greater along the more sheltered of the 2 flanks of the beach, if the waves were coming in at a considerable angle with its central sector. This is illustrated by the lower diagram (fig. 47), where the height of the breakers to be expected would only be about half as great at the point B—other things being equal—as at the point C. And the more abrupt the curvature of a beach is, the more likely it is that the angle at which the waves are coming in will be so great, off one or other of its flanks, that the reduction of breaker height by refraction will be considerable there.

It is necessary, however, to remember that this tendency for a wave to decrease in height, as it is refracted around toward the coast, may be more than offset by the opposite tendency, i.e., for it to increase in height, as it advances shoreward over the shoaling bottom. These two opposing tendencies must therefore be balanced one against the other before one can judge whether landing on an open curving beach will be aided much by refraction at any given time. Under the circumstances that are illustrated, for example by the upper diagram in figure 47, any reduction by refraction would be more than counterbalanced in that way, unless the waves were steeper than about

25:1 to begin with, so that the waves 6 feet high in deep water and 250 feet long would produce breakers at least 6.5 to 7 feet high at A, and 6 to 6.5 feet high at B and at C. But waves of that same

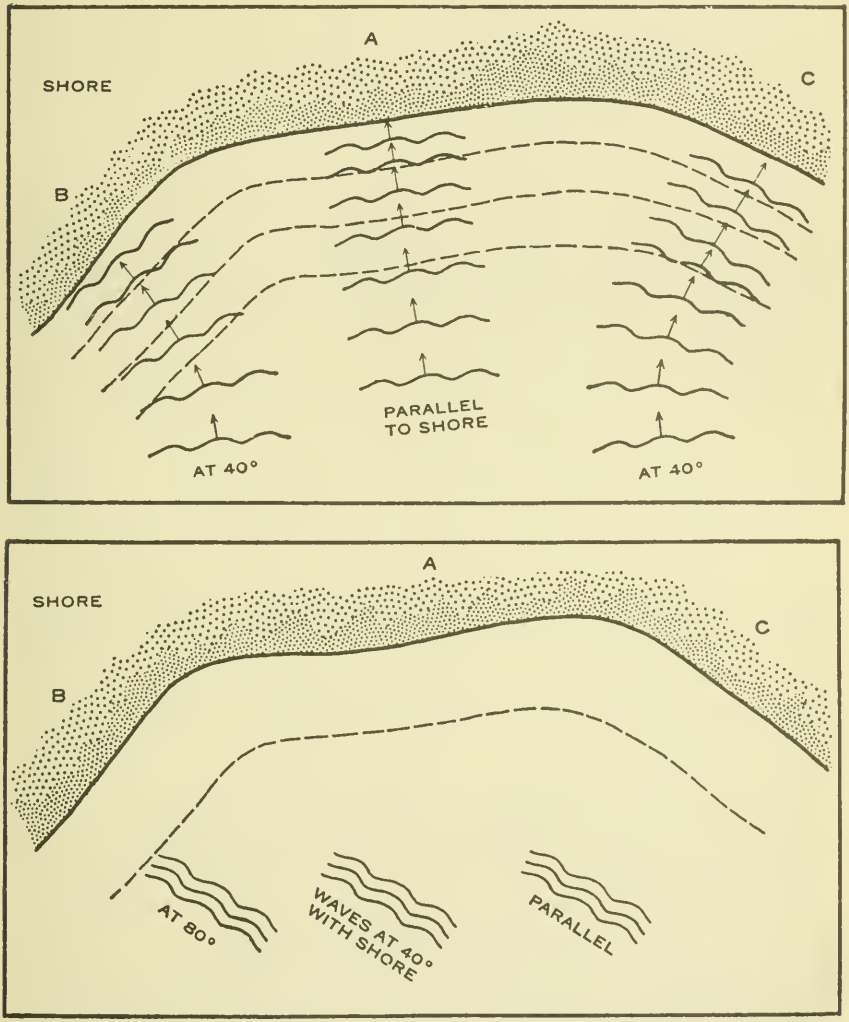

FIGURE 47.—Diagram of a short, rounded beach with waves advancing parallel with its central sector (above), and at an angle of 40° with its central sector but parallel with one of its flanks (below)

height offshore, but 100 times as long as high (as swells often are), might be expected to rise to heights of nearly 8 feet at B and at C, as contrasted with a little more than 9 feet at A.

These examples illustrate the general rule—well recognized by persons who have to do with surf—that when the wave crests offshore

are approximately parallel with the coast of the central sector of a short, wide, and evenly rounded beach (and sandy beaches usually do face the prevailing direction from which the largest waves come), the breakers are not likely to differ enough in height around its shoreline for landing to be easy anywhere along it, if the surf is dangerous along its central part. When the waves are advancing on a beach of this shape at a wide angle—or advancing directly on a more deeply concave beach—the reduction in the heights of the breakers by refraction may be great enough to make landing possible on the more sheltered flank in the one case, or on both flanks in the other case, if the waves offshore are steep and not more than 6 feet or so high. But this is not to be expected if they are much higher than that, or if they are the product of a swell, the initial steepness of which is small.

The situation is different for long, narrow bays, where there may be no surf at all at the head, even when the waves driving in are so large that they cause heavy breakers at the mouth on both sides. We believe the reason to be that the ends of the wave crests break more or less along one or both shores in their advance up the bay while their central sectors are still far away from the head of the bay. And since the waves expand sidewise to compensate for being "worn off" in this way at the two ends, they decrease correspondingly in height. If a bay of this character is long enough, compared to its breadth, the waves may be drained of so much of their energy in this way that they cause only a weak swash on the shore by the time they arrive at the head, i. e., just where the surf is usually heaviest in a crescent-shaped bay. In this connection, we think of St. Mary Bay, Nova Scotia (fig. 48), which is about 8 miles broad at its entrance by about 30 miles long, but which offers safe anchorage and easy landing for small boats at its head at most times, although it is wide open to storm seas, or to swells coming from offshore. And many other long, narrow harbors in various parts of the world owe their safety to their shapes, in this same way.

This generalization might seem (at first reading) to contradict the statement, commonly made, that waves, running up a narrow, funnel-shaped, and steep-walled indentation of the coast, are condensed sidewise as the sides of the cove draw together, so that their heights are increased. Indeed the waves should (theoretically) double in height by the time they reached the point where such a bay was only one-fourth as wide as at its entrance, provided that its bottom were deep and perfectly level from side to side so that the shapes of the waves were affected by the shape of coast, alone. The breakers that sometimes spout in the air at the head of a narrowing chasm, in a rocky coast, afford a spectacular illustration of this principle. And the difficulty of landing may increase, for this reason, toward the head of a very narrow and steep-walled cove, into which a sea is heaving directly. But

this effect is not often of practical importance otherwise, because the bottom usually does shoal toward either side of a bay, whether the latter be broad or narrow, so the waves, being refracted around, break all along the shore and lose in height more than they gain in their run up the bay.

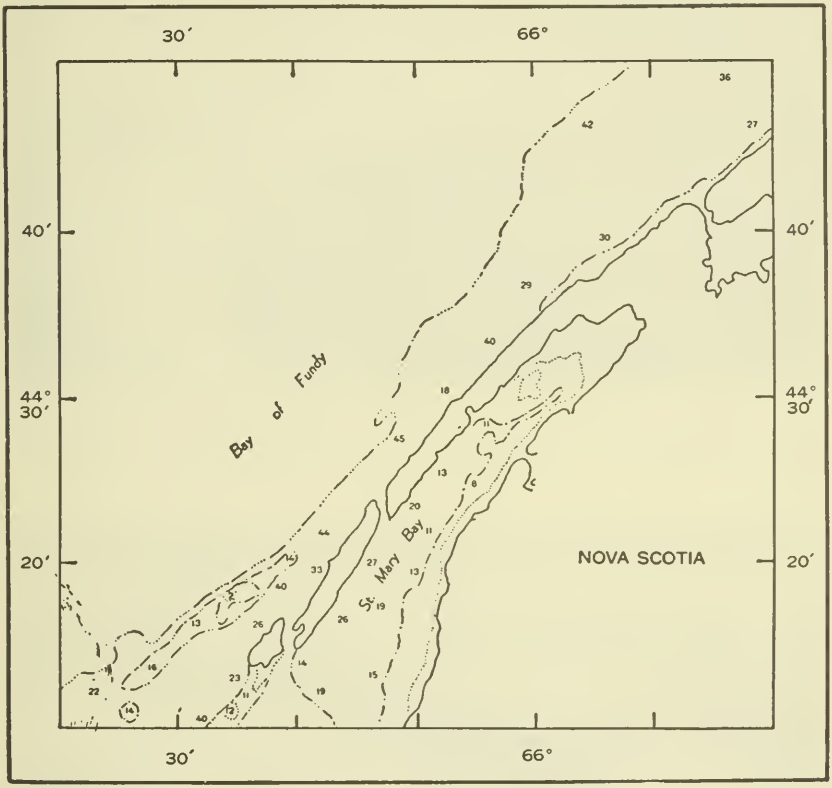

FIGURE 48.—Chart of St. Mary Bay, Nova Scotia. Soundings in fathoms.

SURF AROUND HEADLANDS

It has been stated that when the waves are advancing directly toward a promontory in the direction of its main axis, they are focused more or less on its tip, so that the surf is more severe there (figs. 49, 50) than it would be on a straight coast line, with waves of the same size, and coming in parallel with the coast. But this is true only where the water off the headland in question is so shallow, and the waves running at the time are so long, that they are refracted enough to make them advance upon it from the two sides, as well as against its tip. Sand spits illustrate this, as do higher headlands that are fronted by sloping beaches or by boulder zones, as many are. And it is seldom,

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FIGURE. 49—Surf around a low-lying projection of the Hawaiian coast and on the neighboring beach. (Photograph, courtesy of Mrs. William E. Schevill.)

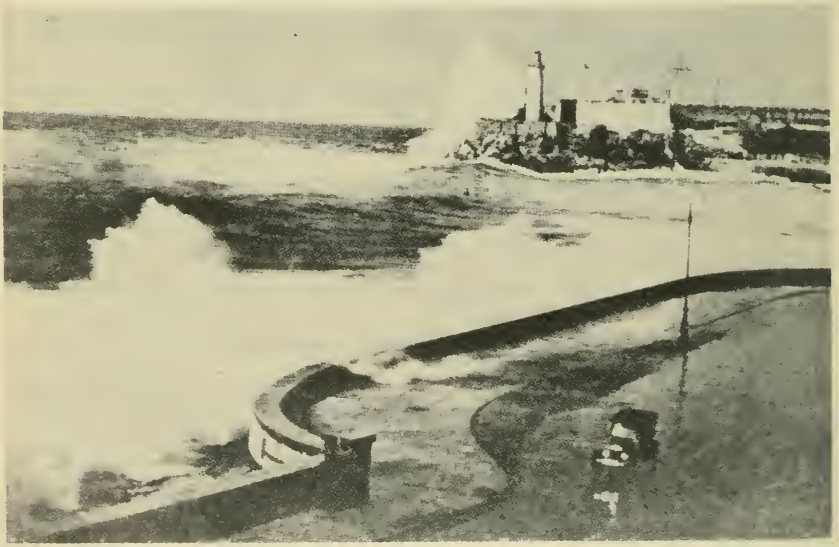

FIGURE 50.—Surf dashing against the eastern headland at the entrance to Havana Harbor, Cuba, on a windy day, as viewed from across the narrow entrance. (Photograph, courtesy of American Photo Store, Havana.)

if ever, possible to land small craft under these circumstances, if the waves are more than 3 or 4 feet high or so. But there are many rocky headlands, close in to which the water is several feet or fathoms deep, even at low tide. And in such cases waves, advancing directly, may be refracted so little that the breakers are not apt to be as heavy on the tip of the headland as along its flanks. In extreme cases of this sort, the inshore ends of waves that are low and short may not be visibly refracted at all, as they run in by the flanks of the headland, either breaking along the latter, if the shoreline is a broken one, or simply rising and falling along it, if the rocks are both smooth and steep. In such circumstances, there may be no regular breakers at all on either flank of a rocky promontory, though a low sea may be producing a surf of moderate size on a beach nearby. But a heavy surf may be expected, not only on the beach, but on both its headlands as well, in stormy weather, because the waves are then so much higher and so much longer that they break in much deeper water. It chances that we are personally familiar with a location of this sort, where we have long watched the varying state of the sea and of the surf with much interest. We should point out, however, that mere absence of surf along a rocky shore does not necessarily mean easy landing there, for it may need only the rise and fall of the water level of only a few feet, with the passage of successive crests and troughs, to render it difficult to embark or to disembark from a small boat—especially since these conditions are apt to exist only when the rocks are both so steep and so smooth that it is not easy to find foothold. If the rocks are more broken, the waves are sure to be breaking there, more or less violently, according to their sizes and according to their direction of advance.

The degree to which the one side of a promontory will be protected, when the waves are coming in against its other side, depends chiefly on how abrupt the alteration is, in the direction of the coast, from the more exposed side to the more sheltered. The inshore ends of the waves may be refracted right around a short headland with broadly rounded tip, no matter from what direction they come, if it fronts on a sloping bottom, and may thus be directed up a bay or harbor, where better shelter might be expected, if one were to judge from the direction of the wind alone. Marblehead Harbor, Mass., affords an illustration of this for it sometimes suffers from swells from the east through southeast to south in this way, although it actually faces about northeast. And Gloucester Harbor, facing a little west of south, was plagued similarly during storms from northeast, east, and southeast, until a breakwater was built for its protection. Rollers may even follow around the shore line until the breakers resulting from them may run directly against the wind, if the coast gradually falls back far enough to bring the wind offshore, a phenomenon de-

scribed more than a century ago. And situations of the sort are not uncommon. In situations, however, where the direction of the coast alters abruptly, and when the waves are advancing at an angle of more than, say, 90° with the sheltered side of a promontory, the refraction of their inshore ends may expand their crests sidewise so suddenly and so widely, (as illustrated in fig. 51), that the resultant breakers decrease abruptly in height as they pass inward along the lee shore. And the actual loss of energy from the inshore ends of the

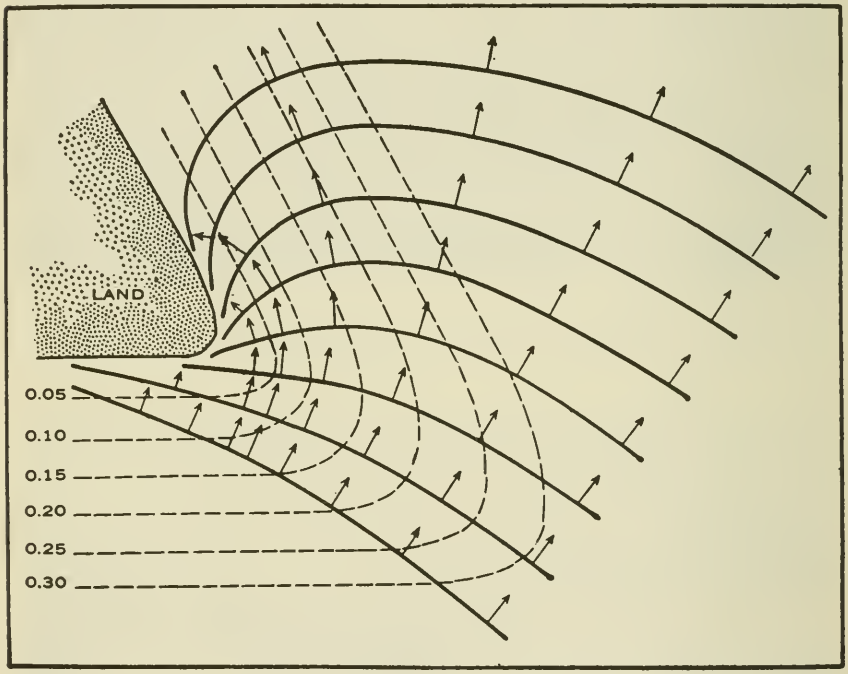

FIGURE 51.—Diagram to illustrate the refraction of waves around an abrupt corner of the coast, when the wave crests in deep water form angles of about 35° with the more exposed shore and of about 155° with the more sheltered shore. The depths of the bottom contours are given in terms of the offshore wave length. The arrows indicate the lines of advance of the waves at successive points along their crests.

waves, as they break, tends to reduce their heights still further, as they continue their advance, just as happens along the shores of a long, funnel-shaped bay (p. 162).

Short waves may, indeed, suffer so little refraction, as they pass an abrupt alteration in the trend of a coast where the water is moderately deep close in to the tide line, that they do not follow around to the more sheltered shore at all, but continue right on past the corner, and so out into deeper water again, leaving what may be termed a "shadow zone" of quiet water, which may be of considerable extent, along the

more sheltered shore behind them. Shadow zones of this sort are commonly to be seen in the lee of steep headlands in moderate weather, as we have observed; they are also found in the lee of steep-walled islets, and of ledges that rise from a comparatively level bottom where the water is deeper than, say, twice the height of the waves at the time. But they are largely or entirely obliterated in heavier weather, because the waves are then so much longer that refraction alters their lines of advance out in much deeper water.

The precise interplay of factors that determines just how much protection from surf may be expected behind a projecting corner of the coast is thus as varied as are the shapes of coast lines, the angle with the coast at which the waves may be advancing, and their sizes and shapes. But the general picture that results from theory and observation combined, is clear enough to allow the following generalizations:

a. The more abrupt the alteration in the trend of the coast and the greater, and the wider the angle between the oncoming waves and the more protected stretch of shore, the more shelter one may expect there from the surf, under a given condition of wind and weather.

b. If the angle between the oncoming waves and the more sheltered stretch of coast is much more than, say 100°, one can expect a very abrupt decrease in the height of the breakers, within a very short distance inward from the corner.

c. The farther in one goes from the corner along the more protected shore, the lower may one expect to find the breakers.

The shelter afforded by a projection of the coast line is greater still if its more protected side is broken by lesser headlands and by coves, because these tend, further, to break down any rollers that may follow in along the shore.

If the alteration in the trend of the coast is not only abrupt, but is through so wide an angle that the two sides of the promontory are nearly parallel, one with the other, as is true of a narrow spit, or of a breakwater, the inner side may be so fully protected that landing is easy there, and out nearly to the extreme tip, even when a heavy sea is running directly against the exposed side. And the inner ends of the waves may not be refracted around sharply enough to touch the inner shore at all, if the alteration in direction of the coast is sufficiently abrupt and if the submarine slope is steep enough, as already remarked (p. 166).

Enclosed harbors and lagoons that connect with the open sea through narrow channels, as between pairs of spits, or between breakwaters—also the lagoons of coral atolls—are fully protected from surf, no matter from what direction the waves may be coming, nor how high they may be, for once the crests have passed through the

cut, the only limit to their sidewise expansion, as they advance across the basin, is such as is imposed by the sides of the latter. The relationship between the breadth of a basin, and the degree to which entering waves are reduced in height as they spread sidewise within it may be illustrated by the Duluth Harbor opening on Lake Superior (fig. 52), where measured waves that were 9.9 feet high at the nar-

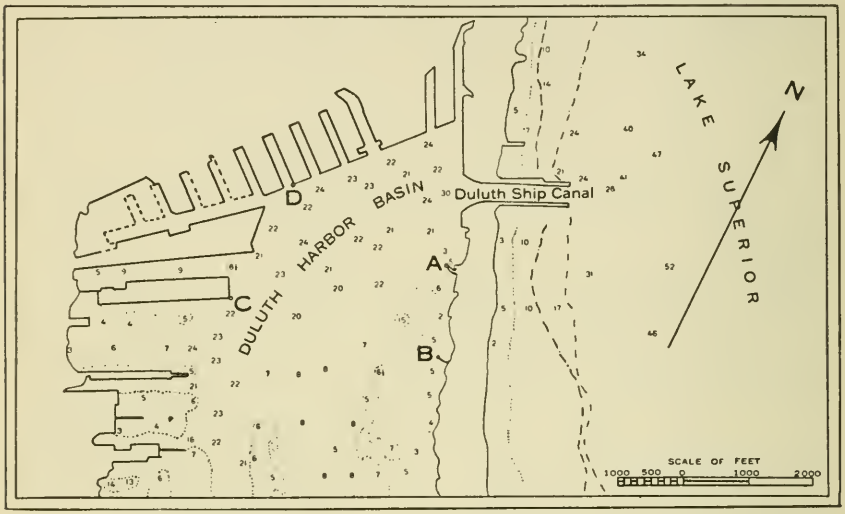

FIGURE 52.—Sketch map of Duluth Harbor. Soundings in feet. (After Gaillard.)

row entrance were only 1.17 feet high at the station marked A on figure 52, and 1.0 foot high at station B; while waves that were 11 feet high at the entrances were only 0.45 foot high at station C, the distances in from the entrance to these stations being 1,200 feet, 2,600 feet, and 4,195 feet, respectively. But waves that were 9.9 feet high at the entrance were still 2.5 feet high at the station marked D on the narrow side of the harbor (a reduction of only 3.6 to 1 in a distance of 3,857 feet) because there is so little room for the wave crests to expand sidewise in that direction (Gaillard, 1904, p. 89).

The rate of reduction in wave height that is to be expected in localities of this sort is calculable, according to Gaillard, by a formula that takes account of the breadth of the entrance (for this limits the breadth of the wave crests that pass through it), the heights of the waves as they emerge from the entrance, the sidewise breadth of the harbor at the place of observation, and the distance of the latter inward from the entrance.

SURF AROUND ISLANDS

The factors that determine the differences in heights of the breakers from place to place along coasts in general, act in the same way around

the shores of islands, whether large or small. Thus, the waves are likely to be focused, as it were, on the exposed side of an island that is rounded in outline if it rises from water shoal enough to alter the direction of advance of the waves to any considerable degree (fig. 53). Consequently, just as at the tip of a headland (p. 163), a worse surf

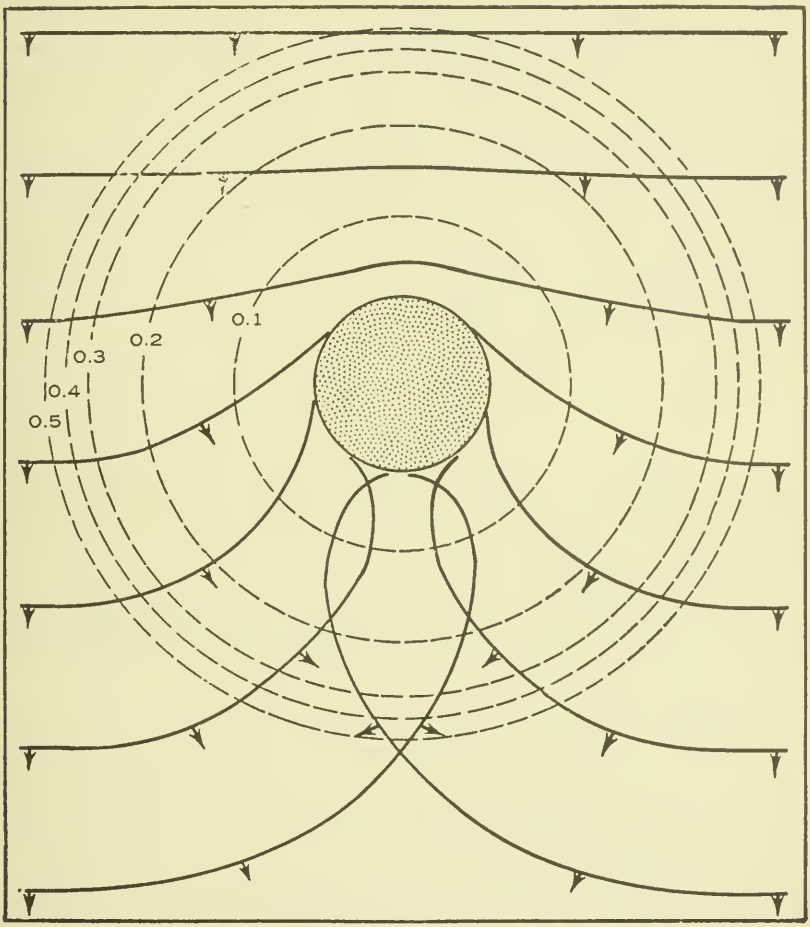

FIGURE 53.—Diagram to illustrate the refraction of waves around a circular island that is surrounded by an evenly and gently sloping bottom. The depths of the bottom contours are given in terms of the offshore wave length.

may be expected there with a given wind than would develop on a straight coast. But while the waves are often refracted right around a small island of this shape, the heights of the breakers they produce will decrease following around the shore, as their inshore ends are delayed more and more by the effect of the bottom. Theoretically, the inshore ends of waves, that were initially 20 to 100 times as long as

high, should break at angles of about 16° to 35° with the part of the shore that was at right angles with their crests offshore, assuming that they did so where the depth was equal to 1.3 times their own heights at breaking, while their heights would be reduced by a little more than one-half there accordingly, as compared with the most exposed part of the island. Observations suggest that the reduction in height might actually be of about this general order of magnitude. Theoretically, too, the inshore ends of the waves should lose still more in height by the time they reach the more sheltered side of the island. However, landing is not apt to be as much easier there as this might suggest, especially if the island is small, for the following reasons:

a. Since the inshore ends of the waves are still at a considerable angle with the coastline when they break, and since the coasts of round islands are usually rocky, bouldery, or strewn with coral heads, landing is much more difficult for practical reasons, than it would be if waves of equal height were breaking parallel with the shore, and if the latter were sandy or pebbly.

b. Although the reduction, by refraction, in the heights of the waves around a small circular island is greatest on the most protected side, the surf may be made very confused there because of the interference that often develops between the two trains of waves that meet, as they are refracted around from the two sides. We ourselves have vivid memories of attempts to land on rocky islets that were unsuccessful for this very reason.

In short, the chance is not very good of landing anywhere around the shore lines of a small rocky island that is circular in form, if the sea is too heavy to allow this on one or other of its two lateral quadrants, and if the submarine contour is such that the waves are refracted right around it. But there may be a shadow zone of quiet water in the lee of an islet, if its shores rise abruptly from water so deep that the waves then running are refracted but little, as they approach it. just as there may be in the lee of a promontory of similar character, and for the same reason (p. 166). But anyone who takes advantage of this to land will be well advised to keep a sharp eye on the state of the sea, and be prepared to put off again at once if the latter rises, for a troublesome surf may develop with astonishing suddenness, as we have often seen.

The more irregular the coast of an island is, and the more abruptly it alters from place to place, the more likely it is that one can find a place in some cove, or in the lee of some headland that will be sheltered from the surf, under conditions of sea that would prevent landing on the more exposed parts of the shore. One or the other of two shallow bights, for example, marked A and B on figure 54, that flank a short promontory on the northern side of No Man's Land, off

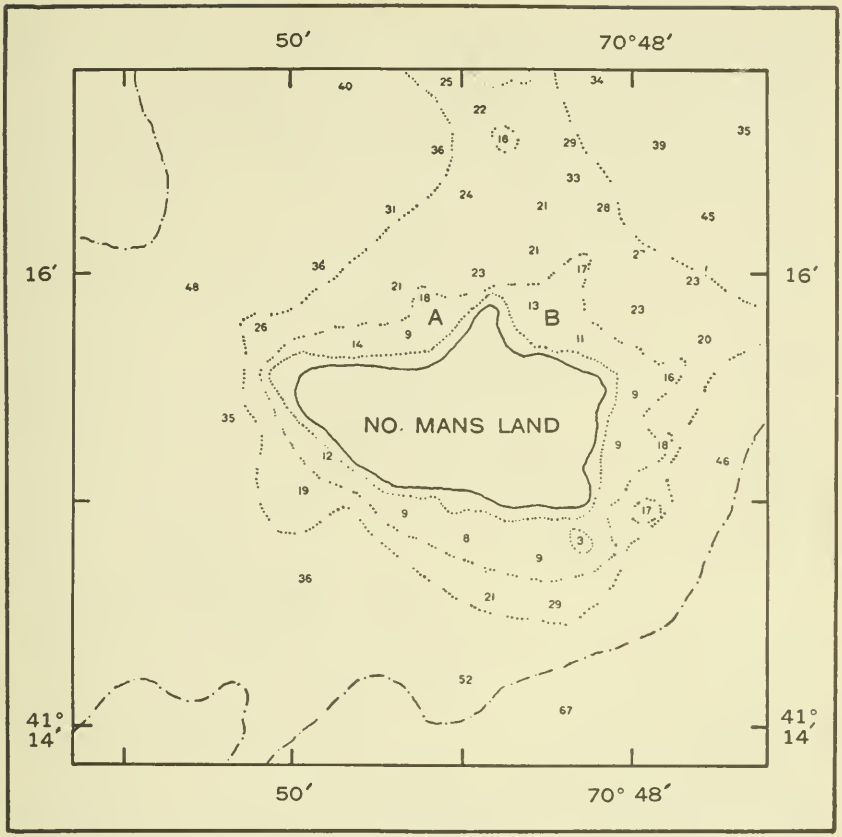

FIGURE 54.—Chart of No Man's Land, Mass. Soundings in fathoms.

Martha's Vineyard, is usually sheltered enough from southerly swells for landing, except in really heavy weather, although the island is only about 1½ miles, east and west, by about 1 mile, north and south, with a very even shoreline, and without any offlying shoals or reefs to break the seas. Similarly, when coaling from one steamer to another was impossible in Cook Bay on the southeast side of Easter Island off the coast of Chile in the third week of December 1904, because of a heavy swell from the southwest, we found La Perouse Bay on the northeast side so protected by Cape Roggewein on the one hand and by North Cape on the other side, that the two steamers could lie side by side in the open roadstead.

A cove on the leeward side of even a small island may, indeed, be perfectly sheltered if the shore line is broken up by a succession of headlands, especially if there are offlying ledges or islets to interfere with the wave pattern. The harbor on the east side of St. Pierre Island off the south coast of Newfoundland (fig. 55) is an excellent example,

being well protected in this way from swells from the southward, southwestward, and southeastward, although it is wide open to the northeast, and although the distance from its entrance to the most easterly promontory of the island is only about 1½ miles.

What was said above (p. 163) about the height of surf around promontories applies equally to islands that are much longer than they

FIGURE 55.—Chart of St. Pierre Island, off the south coast of Newfoundland. Soundings in fathoms.

are broad, especially if they are linear in form, so that the sheltered side of an island of this shape, lying athwart the general run of the waves, may offer excellent anchorage and easy landing, if it is more than a few hundred yards long. The aerial photograph reproduced in figure 45 illustrates this, for an islet with an irregular coast and offlying reefs and beds of kelp; it also illustrates the degree to which a

headland with an offlying islet may shelter a considerable stretch of coast, including the more protected flank of a neighboring beach. And a long, narrow crescentic island with the concavity on the sheltered side, as is true of many sandy islands in regions where the strongest winds are prevailingly from one direction, acts still more efficiently as a natural breakwater. However, if the waves are striking it endwise, no shelter can be expected on either side of it. Sable Island, off Nova Scotia, which is somewhat crescent shaped, with its main axis easterly and westerly and with its concavity on the northern side, provides shelter in this way from southerly swells or seas; but there is no shelter anywhere around its shores if the wind is from any other quarter, in spite of its considerable length (21.5 miles), and even though an extensive bar makes out from each end of it.

The larger an island is, the lower the surf is on its most sheltered side, as a rule, partly because the sidewise expansion of the inner ends of the wave crests is greater around it than in the case of a smaller island, but also because the interference by irregularities of the coast, operating through a longer distance, drains the inshore ends of the waves of their energy more effectively.

We might also remark, in passing, that the presence of an island, of whatever size or shape, may interfere with the regular wave pattern for a long distance to leeward, in regions where long swells prevail. This is illustrated on a small scale by the interference between the wave trains in the lee of the small islet that is pictured in figure 45. The Polynesian navigators of old were acquainted with this phenomenon, and made use of it, not only to direct their canoes from island to island over long distances, but also in their search for new islands.

The preceding account of surf around islands, in general, and around promontories, applies equally to coral atolls, for these are not all circular in shape, as it the common belief, nor even approximately so, but exhibit a wide variety of outlines. Thus, the swell heaves right around Nukuoro Atoll, in the Carolines, during the winter season when the Northeast Trade Winds are at their height, there being no shelter anywhere, except within its entrance, for it is nearly round and only between 3 and 4 miles in diameter (fig. 56). On the other hand, the southerly face of Arno Atoll is so well protected by the long promontory known as Northeast Point (fig. 57) that it affords a safe anchorage and easy landing when the swell is coming from the northeast, though not with swells from any other direction.

Waves that run in through the passages, by which the lagoons of coral atolls are connected with the open sea, expend their energy in the basins inside, at the expense of their heights, just as happens in harbors of similar shape. And it is well known to everyone who has had experience in coral seas that there is no danger from surf once

one is inside the lagoon, no matter how heavy the breakers may be on the exposed faces of the reefs outside, provided only that the contour of the lagoon falls away sharply inside the entrance. If only the one side falls away, this will be the more quiet side, the other the least so. The measurements of waves that have been made in Duluth Harbor (p. 168) suggest, for example, that sidewise expansion would not only reduce waves that were 15 feet high outside to only about 2 feet high

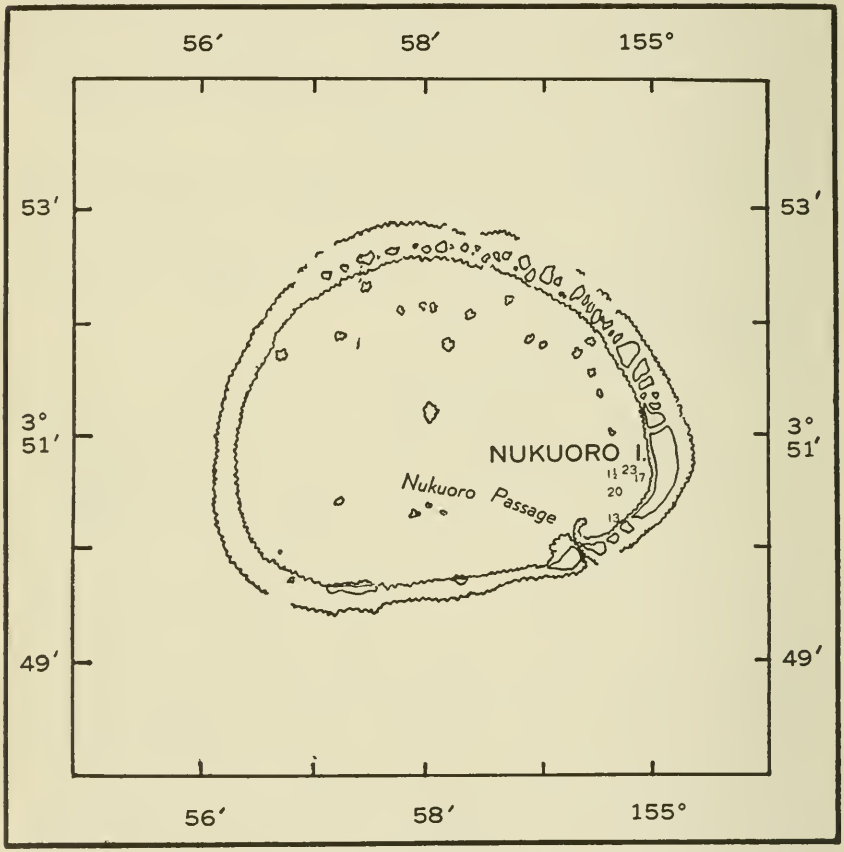

FIGURE 56.—Chart of Nukuoro Atoll, Caroline Group, western tropical Pacific. Soundings in fathoms.

at a distance of a quarter of a mile inwards from the entrance of an atoll as nearly circular as the one charted in figure 56, but would render them imperceptible by the time they had crossed the lagoon, if the latter were so much as ½ mile across. And the waves running in through the passage would be drained of so much of their energy as they broke along its sides that their heights would already be reduced considerably, before ever they reached the lagoon at all.

SUBMARINE TROUGHS AND RIDGES AS AFFECTING SURF

It has been assumed in the foregoing discussion that the submarine contours are more or less parallel to the coast, out to the depth beyond which the waves are not refracted by the bottom. And this is usually the case, at least within broad limits. But the refraction of waves by the slopes of submarine troughs, or of ridges or spits that run out from

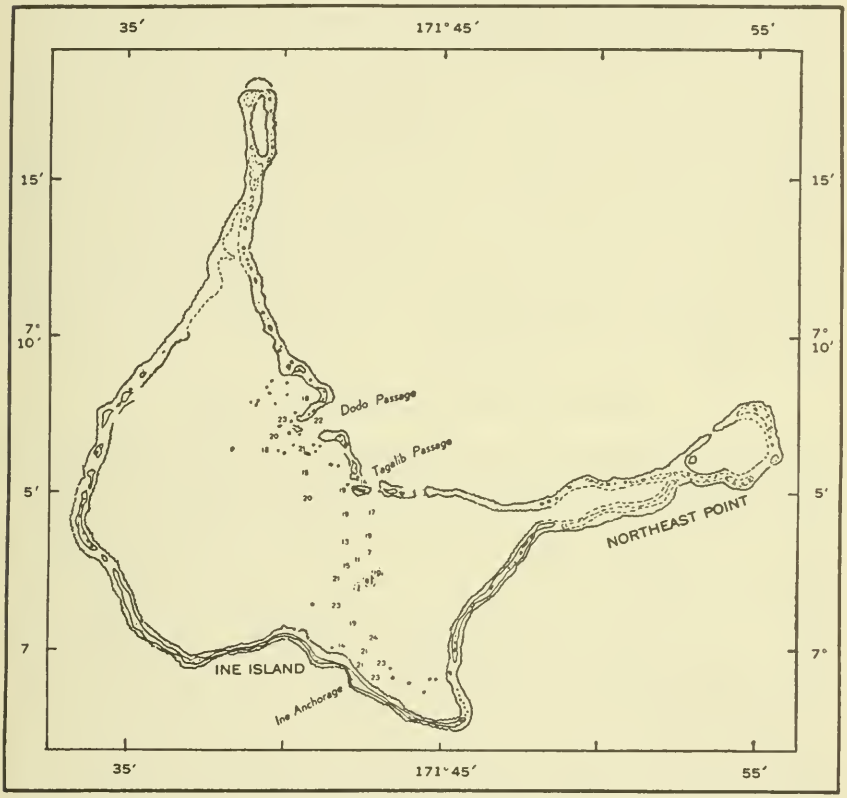

FIGURE 57.—Chart of Arno Atoll, Marshall Group, western tropical Pacific. Soundings in fathoms.

the shore line may also be enough to affect the height of the local surf considerably off some coasts.

In the first of these cases, the wave crests are delayed in their progress along the two slopes of the trough, so that they are refracted around, much as they would be if running into a long narrow bay, whereby their heights may be decreased to such an extent that the surf may be appreciably lower along the sectors of the coast that face the trough than it is on either hand. And the local fishermen on the coast of California, in particular, have long known that a small boat

can often lie comfortably at anchor at the head of a submarine canyon, such as the one off La Jolla, at times when the swell is too heavy for this in the shallower water on either side of it. The surf immediately on the beach may also differ in height accordingly from place to place, or it may even be interrupted altogether, at the head of such a trough.

The effect of a submarine ridge is, of course, the reverse of that of a submarine trough, because waves coming in at right angles to it advance more rapidly along its deeper flanks than along its shallower axis, so that they are refracted toward the latter. If the water on the bar is shoal enough, and if the waves are large enough, they may break upon it, as well as at the extreme tip of the promontory from which it projects. In such cases the surf may be enough lower on the sides of the promontory for a boat to come in in moderate weather. But where the water over the bar is so deep that the waves do not break there, its presence may not only focus them upon the promontory, but the wave trains that run in along its two flanks may produce a cross sea, as they are bent the one toward the other, so that the surf may be heavier opposite the base of the ridge than it is along the neighboring coast on either hand.

FORECASTING BREAKERS AND SURF

Since surf conditions depend directly on the waves coming toward a beach and on the configuration of the bottom off the beach, the state of the surf can be predicated from wind data by predicting the sea and swell as discussed previously, and applying knowledge of the behavior of waves entering shoaling water. The relation between surf and swell has already been discussed on previous pages. A detailed treatment of the prediction of surf conditions has been published by the Hydrographic Office as *Breakers and surf; principles in forecasting.*

Knowledge of the effect of bottom on waves can be applied to show which parts of a section of coast will have the lightest surf under any given conditions of sea and swell. Thus, wartime operations may be planned far in advance and yet take advantage of the most probable conditions. At the time of the landing itself, surf predictions have been found to be very useful. For instance, just before the landing at Gela, Sicily, the seas were very rough in the Straits of Malta, and there was some question among those in command as to whether the beaches would be approachable or not. Consideration of the meteorological situation indicated not only a quick subsidence of the seas, but also that the landing beaches would be somewhat in the lee of the island. On this basis, it was decided to make no alteration in plan, and the landing which followed caught the Italians napping as they had gone off the alert during this period of unusually high seas.

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